Carrier Unlicensed Radios 2018

Wi-Fi, LTE-U, LAA, CBRS, LWA, MulteFire

Abstract:

This report illustrates multiple ways that service providers will use the unlicensed and shared-license bands to offer wireless services. Mobile operators, cable and fixed operators, and Over The Top players are all getting involved, as free spectrum allows them to deploy new LTE, Wi-Fi, and other options for commercial services. This report includes a five-year global forecast.

K. Mun

July 2018

MOBILE EXPERTS

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Carrier Unlicensed Radios:
Carrier Deployments in Unlicensed and Shared Spectrum including Carrier Wi-Fi, LAA, CBRS, and MulteFire Radios

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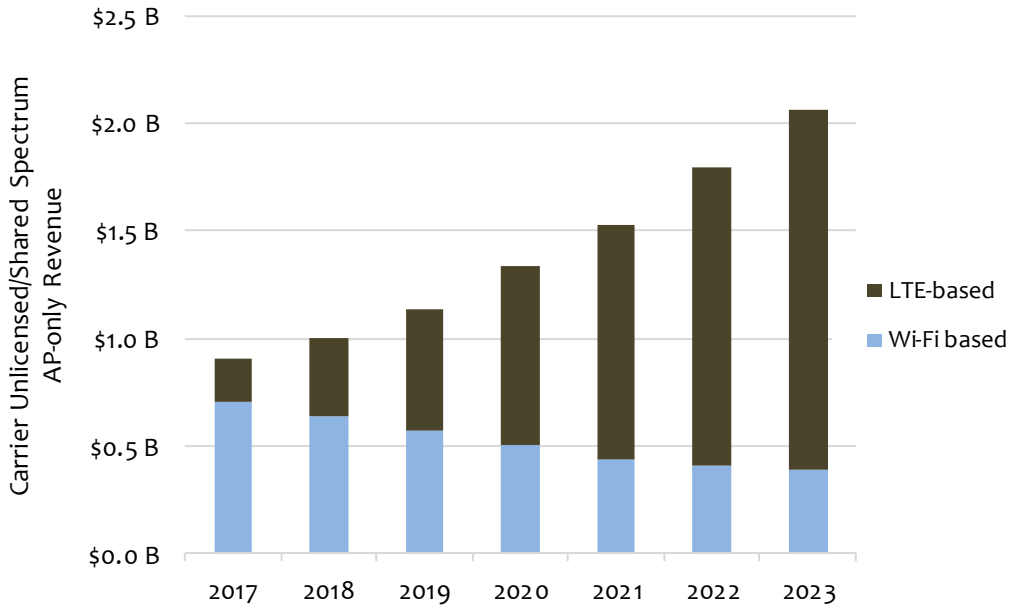
1 EXECUTIVE SUMMARY

The use of unlicensed spectrum for carrier and public services including mobile and nomadic applications has been confined to the Wi-Fi technology through the "carrier unlicensed radio" infrastructure equipment ranging from standalone access point (AP) mounted at outdoor public hotspot locations to customer premise equipment (CPE) at homes and businesses. Over the past several years, the mobile industry has defined several 3GPP standards-based approaches including Licensed-Assisted Access (LAA) for carrier aggregation, standalone LTE use in unlicensed (MulteFire), and LTE use in shared spectrum in the USA (CBRS) to more efficiently leverage unlicensed spectrum. The "LTE-based" carrier unlicensed radio equipment, market, including LAA, CBRS, and MulteFire, is forecasted to grow quickly to over $1.6B in 2023, growing from just over 22% share of the overall Carrier Unlicensed Radio market (for mobile and nomadic applications) to over 80% in 2023. With the large base of Wi-Fi integrated CPEs shipping in hundreds of millions, the Carrier Wi-Fi infrastructure market will remain stable around $8B.



Source: Mobile Experts

Chart 1: Carrier Unlicensed Radio AP Equipment Revenue Forecast, 2017-2023

Conversely, the LTE-based unlicensed and shared spectrum technologies--like CBRS and MulteFire--will not meaningfully impact the Enterprise WLAN market. Mobile Experts expects CBRS and MulteFire technologies to open up new market opportunities in "private LTE" and IoT applications. The LTE-unlicensed use in the Enterprise WLAN market will not be a "zero-sum game." We expect the Enterprise WLAN market to grow 36% in 2023 from its 2017 level.

With mobile operator preference for LTE-based solutions, the standalone AP segment of the carrier unlicensed radio infrastructure market is expected to trend down in the near term. The cable operators and other OTT providers like fixed wireless ISPs in rural areas will continue to adopt Wi-Fi as they transition to 802.11ax. The mobile operators will use LAA in "hotspot" locations to increase network capacity—for "Gigabit LTE" services. The shared spectrum use in the 3.5 GHz CBRS band in the USA is expected to bring diverse group of service providers, and the cable operators are expected to be active users of this band for mobile services.

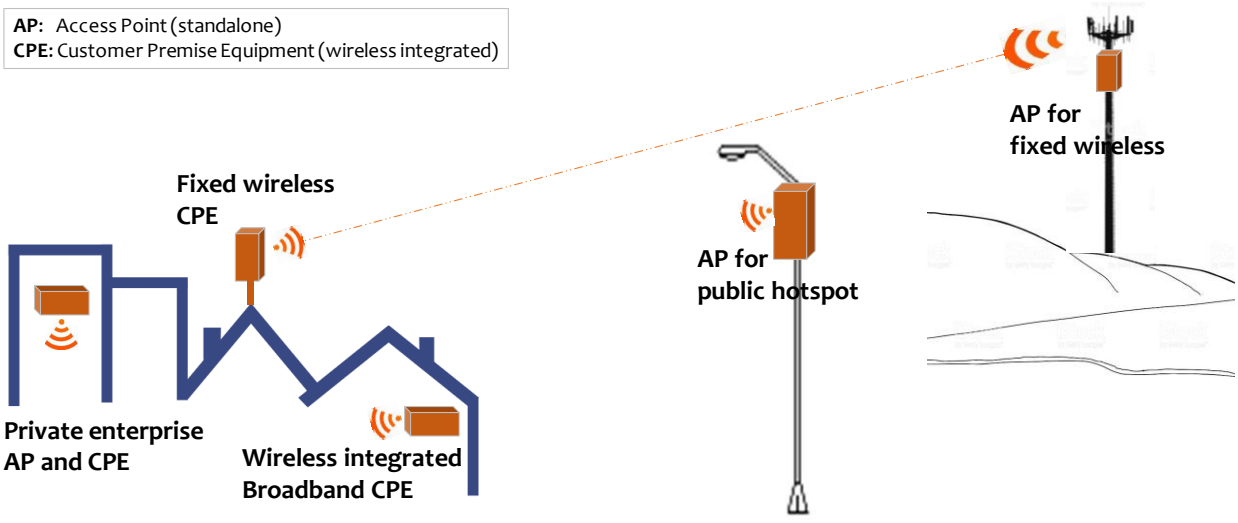
The unlicensed and shared spectrum segment of the carrier infrastructure market is undergoing a rapid change as new technologies, new spectrum, and heightened competition between cable and mobile operators are incentivizing the different service provider groups to stake a claim. The introduction of LTE-based technologies such as LAA and MulteFire and novel approaches to open up more spectrum under coordinated sharing like CBRS will increase the overall carrier wireless infrastructure equipment market leveraging unlicensed and shared spectrum.

2 MARKET OVERVIEW

Fundamental drivers for carrier infrastructure equipment are data traffic growth and technology transitions to seek higher performance and cost efficiencies. For the carrier wireless infrastructure market specifically leveraging unlicensed (and shared) spectrum, the types of applications also drive equipment volume and technology choice. For instance, the cable operators primarily target home broadband and video users; hence, their choice of Wi-Fi is probably most economical. On the other hand, mobile operators seeking to augment network capacity would probably prefer the unlicensed spectrum access at the radio layer using LTE to keep core network operations seamless. Expanding unlicensed and shared spectrum access from sub-6 GHz to 60 GHz bands through the IEEE (Wi-Fi) and 3GPP (LTE/5G) technology options is enticing a diverse group of operators to augment their wireless network requirements with the carrier unlicensed radio equipment.

"Carrier Unlicensed Radio" Market Definition

Wireless is now an extension of any broadband connectivity service whether that's at home or outdoors. Fixed broadband providers like the cable and wireline telco operators increasingly rely on wireless broadband gateways to service a growing number of wireless devices at home such as smartphones, laptops, security cameras, doorbells, etc. The same is true for small businesses--especially those without IT staff. These small businesses largely look to broadband service providers to manage wireless environment inside their premises. While the carrier use of unlicensed radios like Wi-Fi is largely confined to "local area networks" covering a home, for instance, some fixed wireless operators use outdoor radios to cover a wide area. For some, providing public hotspot coverage using standalone Wi-Fi access points provide strategic value-add for fixed or nomadic services.



Source: Mobile Experts

Figure 1. Broad Carrier Unlicensed Radio Equipment Definitions

As shown above, the carrier unlicensed radio equipment generally covers higher-power access point (AP) units for outdoor applications and wireless-integrated customer premise equipment (CPE) like broadband gateways sitting inside homes and businesses. In some cases, a CPE can be high-power units placed outside for fixed wireless applications, but recently large numbers of CPEs have been used by cable operators to create a network of APs, through millions of "homespots." The sum of these APs and CPEs across the different applications are consider the "carrier unlicensed radios" units.

Strandmount Access Point	Fixed Wireless Access Point	Home Broadband Gateway (CPE)	Indoor Wi-Fi Access Point

Note: The three rightmost images are from Quantenna investor presentation

Figure 2. Representative Carrier Unlicensed Radio Products

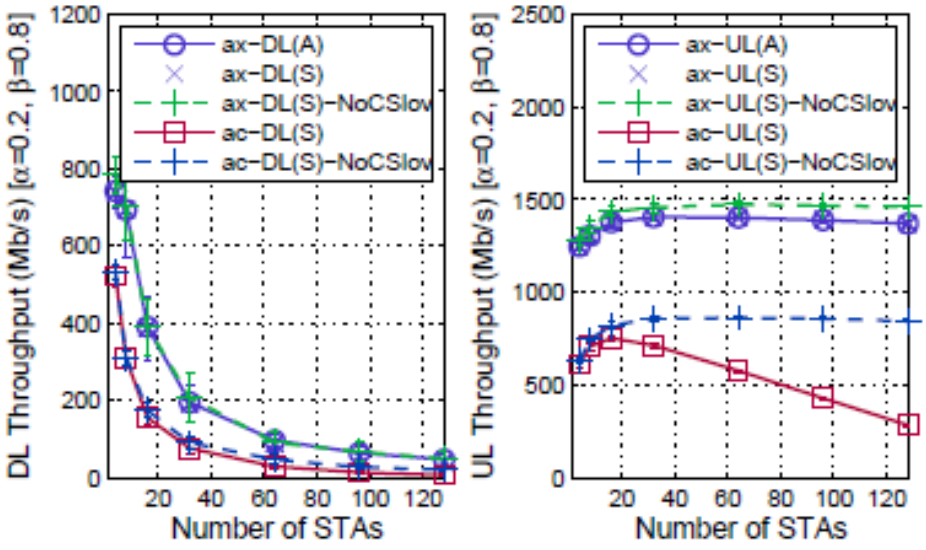
The Carrier unlicensed radio equipment in the form of standalone APs or wireless CPEs can come in a wide variety of form factors and power levels. While CPEs are mostly low-power indoor units for providing wireless connectivity inside homes and small business buildings, most outdoor APs and CPEs are higher-power radios that can provide greater distances for coverage and reach. For example, some 5 GHz unlicensed radios deployed for fixed wireless applications can operate at 4W EIRP in certain U-NII bands. In contrast, indoor Wi-Fi integrated CPE units may operate at 100-250 mW, depending on each country's rules. Some of the wide variety of carrier unlicensed radio products are shown above.

While a "broad" Carrier Unlicensed Radio market can include all aspects of carrier wireless services as depicted in Figure 1, in this report, we specifically target Carrier Unlicensed Radios used for "mobile and nomadic" applications only. Hence, all fixed wireless access related radios[1] and residential broadband gateway markets are not covered in our "Carrier Unlicensed Radio" forecast except for a small portion of small business CPE-related deployments that are used by mobile/telco/cable operators to provide hotspot coverage to its users for nomadic use.

[1] Mobile Experts provides a detailed coverage of fixed wireless market across both licensed and unlicensed spectrum bands using LTE/5G and 802.11-based technologies in our *Fixed Wireless Access* market study.

Right Fit for Carrier Unlicensed Radio

Operating carrier services on unlicensed spectrum can be tricky--especially for wide area outdoor applications. Unlicensed spectrum, by definition, is non-exclusive, meaning that a carrier that uses the spectrum must be cognizant of who else may be operating in the band and how that might impact the service quality. Losing customers due to poor service quality is something that worries every operator. Wireless technologies like Wi-Fi that operate in unlicensed spectrum are thus designed to operate in these unpredictable environments. For example, Wi-Fi technologies through multiple generations from 802.11n to 802.11ac are designed to operate on contention-based manner. If another user operates in the same channel, it must back off and retry. As one can imagine, a channel will become congested as more users operate in a given band. As shown below, the aggregate channel throughput Wi-Fi 802.11ac and 802.11ax operations decreases as the number of Wi-Fi user devices (STAs) increases. As the graph illustrates, a high-density environment (i.e., more users per given access point) is problematic for unlicensed radio operation as the "congestion" brings down the overall data throughput.



(a) DL and UL IEEE 802.11ax and IEEE 802.11ac aggregate throughput as a function of the active number of stations (N) in the WLAN.

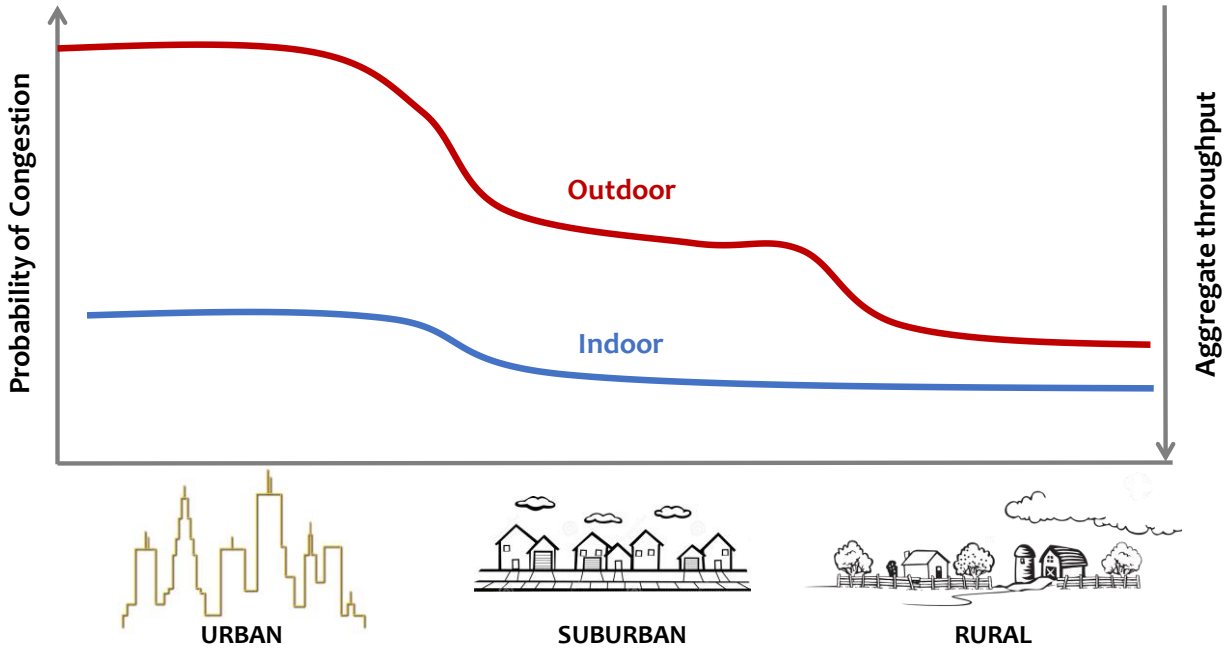
Source: Bella et al[2]

Figure 3. Wi-Fi throughput performance degrades in a congested environment

Taking this principle of avoiding congestion to maximize unlicensed radio operation, we can see that unlicensed radio operation like Carrier Wi-Fi makes sense in certain places and applications as illustrated below. Urban areas are congested places with lots of users and

[2] Bellalta et. al., "AP-initiated Mutli-User Transmissions in IEEE 802.11ax WLANs," June 2018

traffic. With a high probability of congestion, running high-power, wide-area Carrier Wi-Fi operation is probably not well suited. With the probability of congestion declining (i.e., lower user density) in suburban and rural environments, running Wi-Fi may be suitable. For indoor applications like wireless home broadband gateways, the building structure provides reasonable blockage from unwanted co-channel operations from outside. Moreover, low-power operation of the home CPEs can minimize possible interference from adjacent APs. In multi-dwelling unit environment found in urban settings, the probability of congestion is higher due to AP operations across multiple floors. Hence, the probability of congestion for indoor operation in urban settings is expected to be higher than suburban and rural markets. Overall, the carrier unlicensed radio operation in indoor settings is much more suitable compared to outdoor applications.



Note: Illustration only

Source: Mobile Experts

Figure 4. Performance expectation of outdoor and indoor unlicensed radio operation

For tricky outdoor applications especially in urban settings, operators need to take careful precautions like employing sophisticated antenna technologies like MU-MIMO and OFDMA or operate in "uncongested" channels like 5 GHz U-NII-2 and possibly 3.5 GHz GAA when that spectrum opens up.

Expanding Unlicensed Spectrum Horizon

Spectrum is obviously a fundamental resource for wireless services. Unlicensed and shared spectrum resource for fixed wireless access span across from sub-1 GHz to 70/80 GHz

millimeter wave bands. This wide range of spectrum options come with caveats on distance reach and speed performance, AP-CPE cost tradeoffs, "$/GB" transport cost, architecture/deployment choices, core network requirements, and many other factors that impact on-going operations of delivering fixed wireless broadband service. One thing is clear. Spectrum is a key determinant of broadband service level (speed and quality), and cost point at which a particular service is delivered.

Spectrum Band	Bandwidth	License Regime	Technology	Interference Risk	Availability (Region)
2.4 GHz (2.40 – 2.49)	~80 MHz	Unlicensed	Wi-Fi (802.11)	High	Now (worldwide)
3.5 GHz (3.55 - 3.70)	150 MHz	Shared (CBRS)	CBRS, LAA, MulteFire	Medium (GAA)/ Low (PAL)	2018/2019 (USA)
5 GHz (5.15 - 5.85)	580 MHz	Unlicensed	Wi-Fi (802.11), LAA, MulteFire	High	Now (worldwide)
6 GHz (5.925 – 7.125)	1,200 MHz	Unlicensed (PROPOSAL)	Wi-Fi (802.11)	Medium - High	N/A (USA, EU)
60 GHz (57 - 71)	14,000 MHz	Unlicensed	Wi-Fi (802.11 ad/ay)	Low – Medium	Now (NA, APAC, expanding)

Source: Mobile Experts

Figure 5. Unlicensed and Shared Spectrum Landscape

The Wi-Fi Alliance and IEEE standards organizations continue to play integral roles in development and promotion of unlicensed spectrum technologies. Meanwhile, the CBRS Alliance and MulteFire Alliance are active promoters of the LTE use in the unlicensed and shared spectrum bands.

2.4 GHz ISM Band

WISPs have used the 2.4 GHz band in the past to take advantage of a large chunk of spectrum in this band. With the popularity of Wi-Fi use indoors and out, the rising noise floor in this spectrum has made its usage problematic in the past. With most Wi-Fi indoor usage moving to the 5 GHz band, some operators are coming back to the 2.4 GHz band as the noise floor has come down somewhat to make this more useful. Like the 900 MHz band, this band is most often used in very rural areas to reach far away subscribers from a base station access point.

3.5 GHz CBRS Band

The *Citizen Broadband Radio Service* (CBRS) provides for shared spectrum use in the 3.5 GHz band. For the first time, dynamic spectrum sharing rules based on the three-tier licensing regime (as shown below) allows commercial use of the band while ensuring interference protection and uninterrupted use by the incumbent users (i.e., military radars and fixed satellite stations). Under the plan, a *Spectrum Access System* (SAS) maintains a database of all CBRS base stations and coordinates spectrum access among the incumbent and new commercial users. In the three-tier licensing structure, at least 80 MHz of spectrum are designated as *General Authorized Access* (GAA), or unlicensed use, and up to 70 MHz of *Priority Access License* (PAL) are planned to be auctioned off as licensed band shortly.

It should be noted that many WISPs currently use the 3.65 – 3.7 GHz band as temporary "incumbent" users for fixed wireless. By 2020, the use of this particular portion of the band will need to transition under the CBRS three-tier licensing regime.

5 GHz WLAN Band

For many WISPs, the 5 GHz band has been the "workhorse" of delivering fixed wireless broadband access with relatively large amounts of bandwidth available. The 5GHz band spans across several different frequency bands with different usage requirements. For fixed wireless application, many WISPs use "U-NII-2-extended" and "U-NII-3" bands for different reasons. With dynamic frequency selection (DFS), or radar avoidance, requirement, many common Wi-Fi access points typically do not use the "U-NII-2-extended" band. Thus, it is relatively "pristine" unlicensed spectrum upon which to deliver fixed wireless access, especially for operators targeting denser suburban settings. Moreover, this particular band is considered a "worldwide" band as it is designated as unlicensed globally. Hence, it provides a greater market opportunity for vendors to address the global market. Unlike the U-NII-2-extended band, the U-NII-3 band provides a greater transmit power limit. Hence, this is popular among traditional WISPs looking to maximize reach, especially in rural areas where the business case mandates a maximal coverage.

Band	Freq. Range	Bandwidth	Max. transmit power	Max. EIRP
U-NII-1	5.15 – 5.25 GHz	100 MHz	50 mW	200 W
U-NII-2A	5.25 – 5.35 GHz	100 MHz	250 mW	1 W
U-NII-2B	5.35 – 5.47 GHz	120 MHz	Not used in unlicensed access	
U-NII-2 extended (*)	5.47 – 5.725 GHz	255 MHz	250 mW	
U-NII-3	5.725 – 5.85 GHz	125 MHz	1 W	4 W

Source: Mobile Experts

Figure 6. 5 GHz unlicensed U-NII band ranges

6 GHz (NEW)

Wi-Fi proponents including Qualcomm, Broadcom, Cisco, WISPs, and others are proposing to have the 6 GHz (5925 – 7125 MHz) band to be "opened up" for unlicensed use, similar to the adjacent 5 GHz band used for Wi-Fi. The band is primarily used by "Fixed Service" and "Fixed Satellite Service" earth station uplink services today in addition to some mobile services (i.e., BAS, CARS, LTTS, and OFS) in certain portions of the band. The proponents argue that the Fixed Service operations are high-power, highly directional, outdoor applications which can be well coordinated with mostly indoor Wi-Fi operations at lower output power. The group is proposing to segment the 6 GHz band (in a similar manner to the 5 GHz band) into multiple U-NII bands as follows in order to protect specific incumbent users of the band.

Band	Freq. Range	Bandwidth	Incumbent use	Max. EIRP
U-NII-5	5.925 – 6.425 GHz	500 MHz	Fixed Satellite uplink	??
U-NII-6	6.425 – 6.525 GHz	100 MHz	Mobile BAS, CARS, LTTS, OFS	??
U-NII-7	6.525 – 6.875 GHz	350 MHz	Not used in unlicensed access	??
U-NII-8	6.875 – 7.125 GHz	250 MHz	Mobile BAS, CARS	??

Source: Mobile Experts

Figure 7. Proposed 6 GHz unlicensed U-NII band ranges

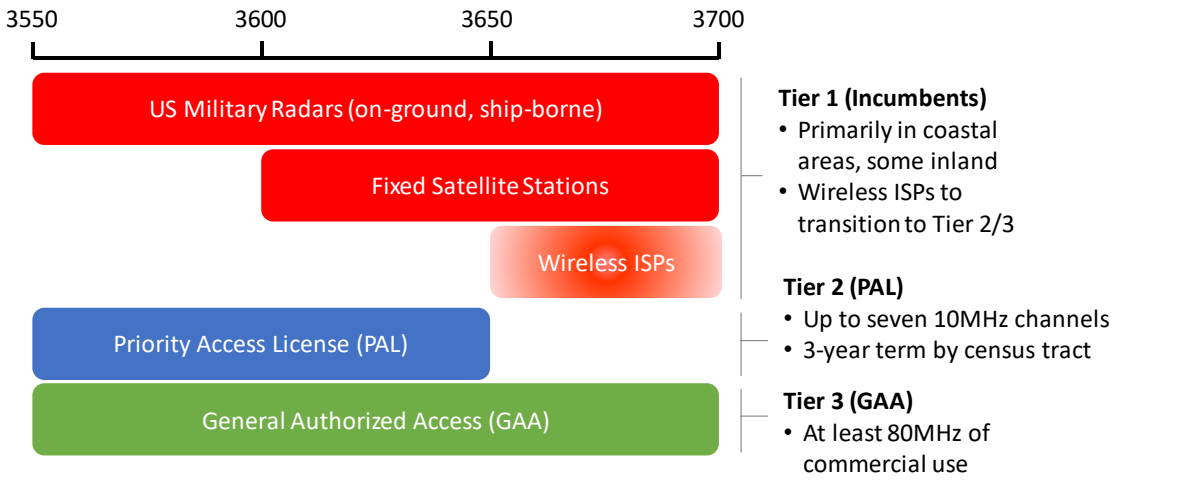
Obviously, Wi-Fi proponents are arguing for less restrictive UNII-3 like regulation, thus permitting diverse applications from outdoor fixed wireless to indoor enterprise wireless networking. Some major operators like AT&T have sounded the alarm in unlicensed use in the band, stating critical infrastructure use in the band. It is unclear as to how the FCC will decide in the fate of the unlicensed use of the 6 GHz band. IEEE 802.11ax users have already presumed that they can operate in this particular band under the proposed U-NII rule. Gaining even portions of the 6 GHz band will be a windfall for the Wi-Fi proponents. If major carriers concede some portions of the band for unlicensed use, Carrier Wi-Fi deployment for indoor applications through CPE will certainly take advantage of the spectrum if and when that happens.

60 GHz Unlicensed

The 60 GHz unlicensed band provides a tremendous amount of spectrum bandwidth – 14 GHz! With a high oxygen attenuation in the 60 GHz band, the use of this band for fixed wireless is confined to short-reach distances, less than 300 meters. While this band has been used in point-to-point (PtP) context for many years, many vendors are developing point-to-multipoint (PtMP) systems to take advantage of the large swath of spectrum for high-speed broadband access in urban and suburban settings. Many vendors, including Nokia, Siklu, Intracom and others, provide PtMP solutions operating in the 60 GHz band. Because of high attenuation and short reach, the 60 GHz PtMP solutions will require outdoor antenna deployment and high-gain beamforming capability to enable fast installation and activation. The industry push into the millimeter wave bands as a part of the 5G transition has enlarged the 60 GHz ecosystem and has expanded the market opportunity in the 60 GHz space including the fixed wireless application.

CBRS - Opening New Bands under Shared Spectrum Rules

Considering that a major US mobile operator holds, on average, roughly 130 MHz of licensed spectrum, the 150 MHz of new spectrum in the 3.5 GHz CBRS band is a significant amount of spectrum for further mobile capacity expansion. In addition, the flexible three-tier licensing framework is expected to lower the barrier and promote success-based investments by new entrants. (Please see the below section on CBRS for the details on how the three-tier licensing works.)



Source: Mobile Experts

Figure 8. CBRS Three-Tier (Shared Spectrum) Licensing Structure

The innovative three-tier licensing structure of CBRS opens up new use cases; and, encourages business innovations from traditional operators and new entrants alike. Here is a list of possible opportunities that CBRS can enable for the different stakeholders:

1) Mobile operators can leverage CBRS band as a secondary carrier in LAA deployment to augment network capacity and boost user throughput speed;
2) Cable operators can build LTE networks and leverage that capacity in their MVNO business to minimize or offset MVNO rent costs;
3) Neutral host providers can use CBRS band to stand up LTE networks for in-building wireless services directly to enterprises or to mobile operators for resell;
4) Enterprises can build "private LTE" networks on the CBRS band under GAA or PAL basis with the assumption that PAL licensing costs are not too exorbitant.

The novel three-tier licensing approach encourages the stakeholders to pursue those business opportunities as highlighted above without the burden of high upfront costs for traditional licensed spectrum. Stakeholders will be able to purchase PAL licenses to secure an appropriate amount of spectrum at specific geographic locations to offer wireless services. This type of success-based investment in PAL spectrum licensing attempts to allow efficient use of the band.

There is some discussion about spectrum sharing in the UK.[3] While it is still uncertain as to whether the three-tier CBRS licensing scheme would be adopted in the UK and EU as a whole, but the fact that Ofcom is discussing the possibility of dynamic spectrum sharing is an encouraging sign that perhaps CBRS rule, or a similar coordinated sharing method, would

[3] Ofcom spectrum sharing framework:
https://www.ofcom.org.uk/__data/assets/pdf_file/0028/68239/statement.pdf

be adopted in the UK, and perhaps EU in general. While this possibility exists, our forecast does not account for this in the CBRS forecast.

LTE and 5G in Unlicensed

As mobile operators continue to seek cost-effective solutions to meet growing traffic demand, LTE use in the unlicensed (and shared spectrum) bands through LAA, CBRS, and MulteFire is a welcome relief for the mobile operators. Until the millimeter wave ecosystem matures, the unlicensed and shared bands under 6 GHz represent the near-term spectrum opportunities upon which to run LTE services. In some countries, 5G bands have been identified between 3.5 and 5 GHz. However, in other countries (notably the USA), the lack of C-band spectrum creates a critical need for mobile operators to use unlicensed bands.

With the 3GPP standards completed and device and infrastructure ecosystems quickly maturing, operators have multiple options to leverage the unlicensed and shared spectrum bands with LTE. Taking things one step farther, the 3GPP standards body is already at work to define 5G Unlicensed operations in both Standalone (similar to MulteFire) and LAA cases. Specifically, 3GPP Release 16 work item entails 5G NR based cell operating standalone in unlicensed spectrum that connects to 5G Core Network for private network scenarios.

Economics of LAA, CBRS, and Wi-Fi – Lowering Unit Cost

The economics of leveraging unlicensed spectrum vary by technology, and target use cases. There are many factors that attribute to an operator choosing one technology over others. The decision can vary by specific regions within the operator's footprint as well. For instance, an operator with a limited spectrum holding is more likely to consider LAA small cells to leverage the 5 GHz unlicensed or CBRS bands. On the other hand, an operator with extensive and mature Wi-Fi footprint may consider LWA in order to maximize its Wi-Fi investments. For others with a large inventory of licensed spectrum (e.g., Sprint with 2.5 GHz spectrum), LTE-unlicensed technologies like LAA may offer little value. With the proposed T-Mobile/Sprint merger, the prospect of LAA use at T-Mobile may diminish in the near term, as the combined company may focus on 2.5 GHz spectrum deployment at the macro layer using massive MIMO.

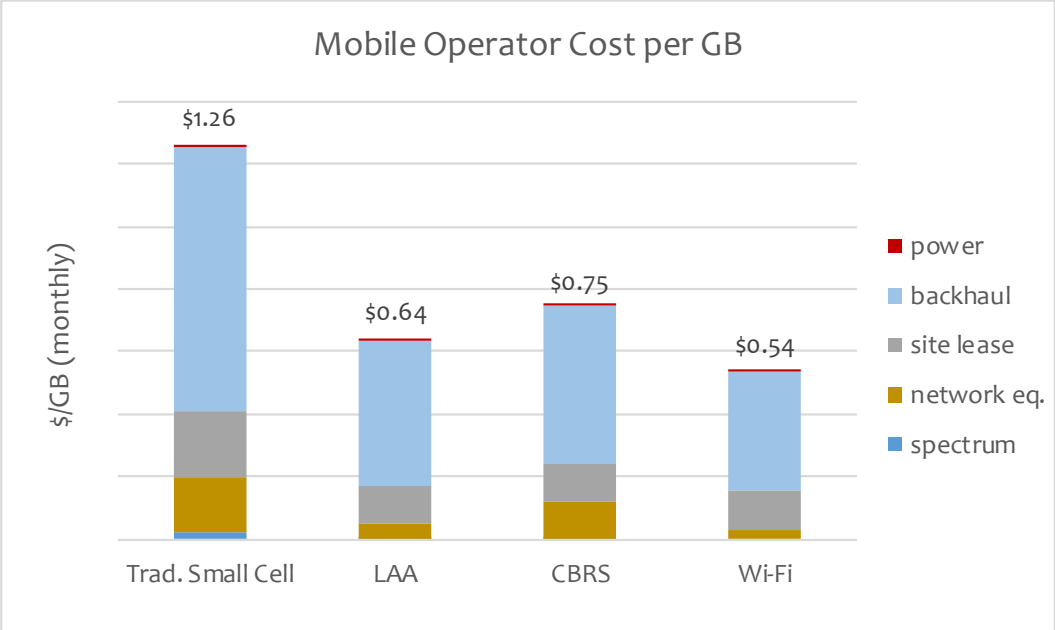
There are many factors to consider in network technology choices, including operational complexity, internal process coordination, device ecosystem impact, etc. Understanding basic unit economics is a good place to start. The below figure shows the unit costs of delivering a Gigabyte (GB) of data over a traditional small cell using licensed spectrum vs. a list of unlicensed technologies including LAA vs. CBRS vs. Carrier Wi-Fi. The unit cost advantages of unlicensed technologies (LAA, CBRS and Wi-Fi) over traditional licensed small cell stem from a simple fact that free or cheap unlicensed/shared bands can be used to increase effective cell capacity. The slightly higher unit cost of CBRS vs. LAA and Wi-Fi, is due to higher equipment cost associated with SAS burdened cost. Overall, the unit cost of

delivering a GB of mobile data using unlicensed and shared spectrum technologies can be about one-half the cost of using a traditional small cell using licensed spectrum.

Mobile Operator Perspective and Choices

Mobile operators in Asia were at the forefront of carrier Wi-Fi deployments in the early days, as they looked for additional avenues to increase their wireless capacity. While Wi-Fi networks have been sufficient for the primary purpose of data offload, the standalone carrier Wi-Fi networks have proven inadequate in providing carrier-grade service quality. Consistency of quality assurance via Wi-Fi has proven particularly elusive in dense environments. To better leverage the unlicensed bands, the mobile industry has drafted 3GPP standards to offer several options to better leverage the unlicensed bands including LAA, LWA, and LWIP---although the prospect of LWA and LWIP scale deployments have largely dissipated.

In terms of simple economics, a mobile operator can almost halve the unit cost of delivering a GB of data by leveraging unlicensed technologies. While the unit cost of delivering data over Wi-Fi is cheaper than LAA or CBRS, Carrier Wi-Fi has not proven to be an effective solution in a Wi-Fi offload setting. Moreover, managing separate LTE and Wi-Fi networks have proven to be cumbersome and operationally inefficient. Factoring in these factors, the total cost of ownership for Wi-Fi may be higher than the simple unit costs as outlined in the figure below.



Notes: 1) Assume that a mobile operator would 100% lease backhaul;
2) In case the operator uses owned fiber/fixed network for backhaul, the unit costs can significantly decrease

Source: Mobile Experts

Figure 9. Mobile Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

Based on trials and market activities in the past year, the mobile operators are moving toward LAA as it allows the operators to run LTE natively in the unlicensed bands without the complexity of network-level integrations required in the LWA case. Moreover, LAA allows the mobile operators to still take advantage of existing LTE core networks including all aspects of service provisioning and delivery. Verizon and T-Mobile in the US have been vocal supporters of LTE-U and LAA. As predicted, T-Mobile has deployed LTE-U in select markets, and is transitioning to LAA this year. Verizon and AT&T are following suit and deploying LAA in select markets as they continue to expand network capacity. For mobile operators, LAA offers the most clear path to run LTE services on the unlicensed bands. It does not impact core networking, and the unlicensed bands can be opportunistically leveraged by deploying LAA small cells and introducing higher category UE devices to aggregate multiple LTE carriers to increase throughput and network capacity overall. Mobile Experts expects most U.S. mobile operators to choose LAA, and the market evidences point to this trend.

After the limited LWA deployments in Asia, i.e., Chunghwa Telecom in Taiwan and M1 in Singapore specifically, we are not aware of any further commercial rollouts. While we initially believed that LWA may be applicable for the mobile operators with extensive Wi-Fi network footprint, such as China Mobile, there is no public evidence of this. We now suspect that the operational complexity of network upgrades from core networking to Wi-Fi and LTE access networks may be too cumbersome and expensive for such deployments to take place. With the Carrier Wi-Fi upgrade cycle taking place every four to five years, some operators may be content to upgrade certain aspects of their Carrier Wi-Fi footprint while upgrading to LAA for those systems that are primarily targeted for mobile use.

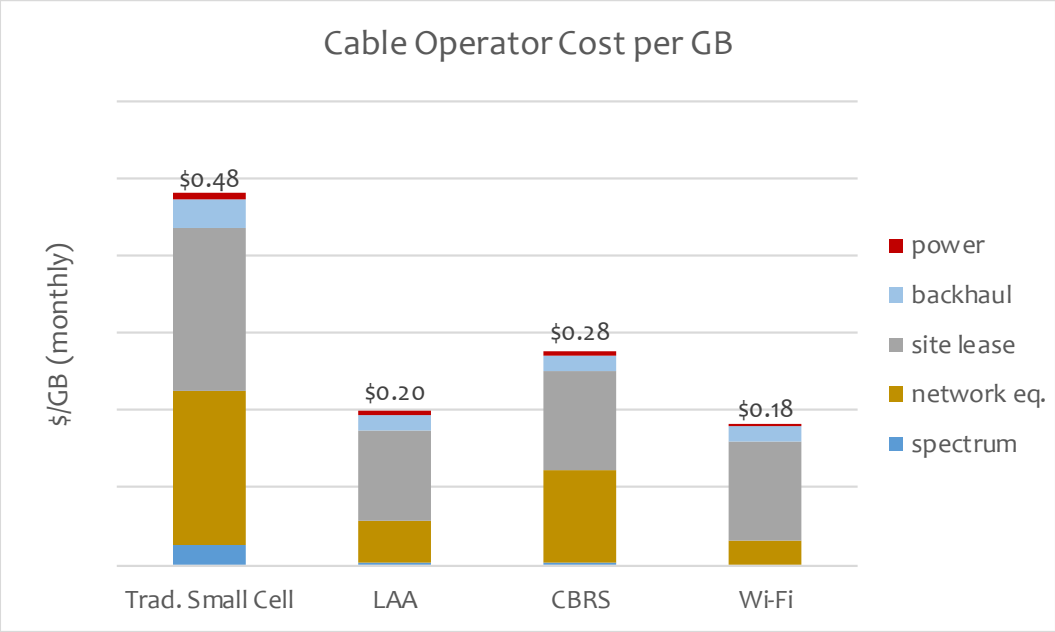
While LWA also offers a means to aggregate LTE carriers over LTE and Wi-Fi infrastructure, it adds additional complexities. Not only do LTE eNodeB base stations need to be upgraded to support LWA, existing Wi-Fi access points must also be upgraded to support the feature. Not only that, UE client devices must also support LWA. All these interdependent upgrades may be too burdensome for many operators. For some operators, especially those in the United States with minimal Wi-Fi infrastructure under operation, deploying LAA as multiband small cell seems to make the most sense. Excluding Sprint, all major mobile operators in the USA have either already launched LAA or is in the process of rolling out LAA in select markets.

Cable / Fixed Operator Perspective and Choices

Cable operators are big proponents of Carrier Wi-Fi. Wi-Fi offers cost-effective wireless extension to their dense broadband networks. To extend the wireless reach of fixed broadband services, cable operators have been placing outdoor Wi-Fi access points mounted on cable strands, on street furniture, and integrated into tens of millions of broadband CPEs at homes and businesses. Although they are committed to the outdoor Wi-

Fi strategy for now, they also seek cost-effective means to run mobile LTE services using cheap unlicensed and shared spectrum. Mobile Experts believes that cable operators will deploy CBRS radios in the 2019-2020 timeframe to take advantage of the new CBRS spectrum for their mobile use to enhance their current MVNO mobile service offerings. The wireless services on CBRS networks may be viewed as "cable wireless" extension beyond the 5GHz band, and possibly as another data offload network for the cable operators' MVNO business.

For the cable operators, CBRS offers lower unit cost. By leveraging owned fiber and DOCSIS networks for backhaul, the unit cost of delivering a GB of mobile data can be cut to almost one-third that of an operator leasing backhaul. In the end, wireless service is about transporting bits. Having owned network infrastructure for backhaul provides tremendous advantages in wireless services as well, especially when one can leverage less expensive unlicensed or shared spectrum for the mobile data delivery.



Notes: 1) Assume that a cable operator would use own fiber or DOCSIS as backhaul;
2) Although a cable operator can theoretically deploy licensed small cells, upfront spectrum cost can be too prohibitive

Source: Mobile Experts

Figure 10. Cable Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

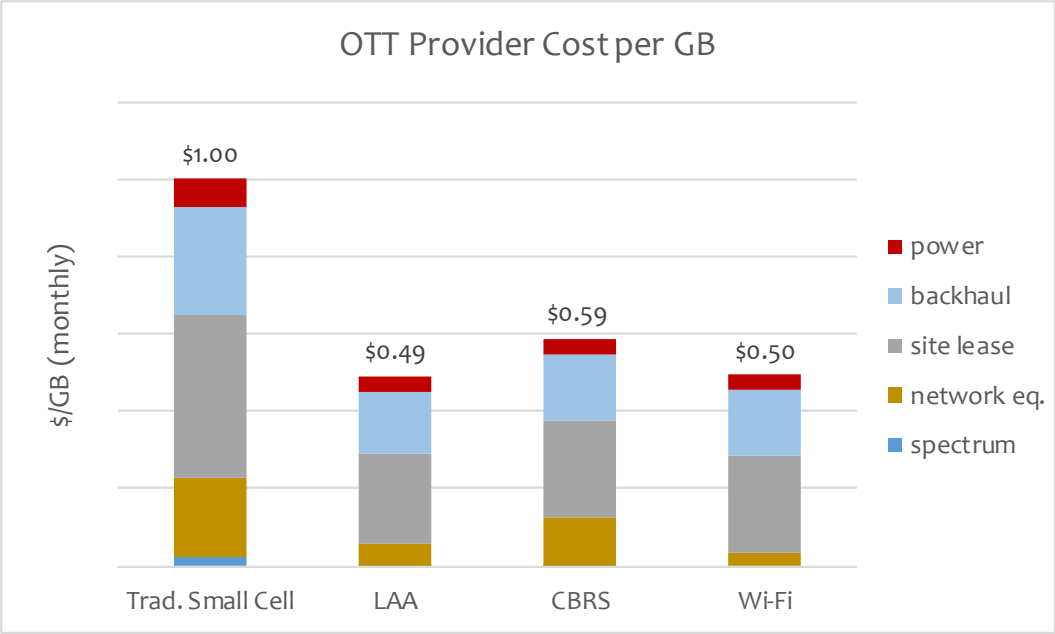
The cable operators view public Wi-Fi hotspots and homespots (i.e., Wi-Fi integrated broadband CPEs at home) as strategic assets in the pursuit of their mobile wireless entry. Using strategically placed hotspots and homespots as a foundation of their wireless footprint, cable operators have been experimenting with various business models ranging from wholesale access to retail wireless services. Comcast's and Charter's MVNO-based mobile service launches portend more expeditious LTE-based network deployments in our view. As an MVNO, they are incentivized to offload subscribers' traffic onto owned

infrastructure to lessen the MVNO rent fees to the host mobile operator (e.g., Verizon in Comcast and Charter's case). It is possible for the cable operators to pursue LAA, but Mobile Experts believes that CBRS is a more likely path for the cable operators as it offers less onerous high upfront cost for licensed spectrum to build up a LTE network.

Over-the-Top / Neutral Host Service Provider Perspective and Choices

Over-the-top (OTT) Wi-Fi operators like Boingo have been providing public wireless service over the unlicensed bands for many years. These providers have focused on strategic public venues like airports to establish a wireless footprint using Wi-Fi. They have typically charged for roaming access to mobile operators or other service providers and per-use fee to retail customers. A good example of a wholesale business model is the Wi-Fi roaming agreement that Boingo has established with Sprint. Under this agreement, Sprint customers automatically roam onto Boingo's Wi-Fi networks at major US airports and use the networks as if they are on Sprint's network coverage. With Hotspot 2.0 profiles pre-installed on Sprint phones, Sprint customers can seamlessly access Boingo's Wi-Fi network services without the typical Wi-Fi authentication login process. While the wholesale Wi-Fi access business can bring a meaningful revenue contribution, it has been tough to convince some mobile operators to use "less reliable" Wi-Fi for mobile services. To the mobile operators, the possible churn from unreliable service quality is a huge risk.

Although its unit cost is slightly higher than Wi-Fi, mainly due to the SAS burdened cost embedded in the network equipment cost, CBRS offers an inexpensive means to stand up an LTE network. Without high upfront costs for spectrum, OTT and neutral host providers can selectively build out CBRS network to serve specific market needs. For example, a neutral host provider can build in-building wireless system based on CBRS small cells to offer LTE network services to enterprises directly or through mobile operators. Assuming that future smartphones distributed through mobile operator channels support 3.5 GHz CBRS/OnGo, OTT service providers can potentially offer more cost-effective in-building wireless solutions than traditional DAS solutions.



Notes: 1) Assume WiGig PTP 60GHz radio deployment for small cell backhaul to lessen the backhaul cost;
2) Assume that WiGig PTP radio gear has a 5-year lifespan;
3) Although an OTT operator can theoretically deploy licensed small cells, upfront spectrum cost is too prohibitive to be realistic (for reference only)

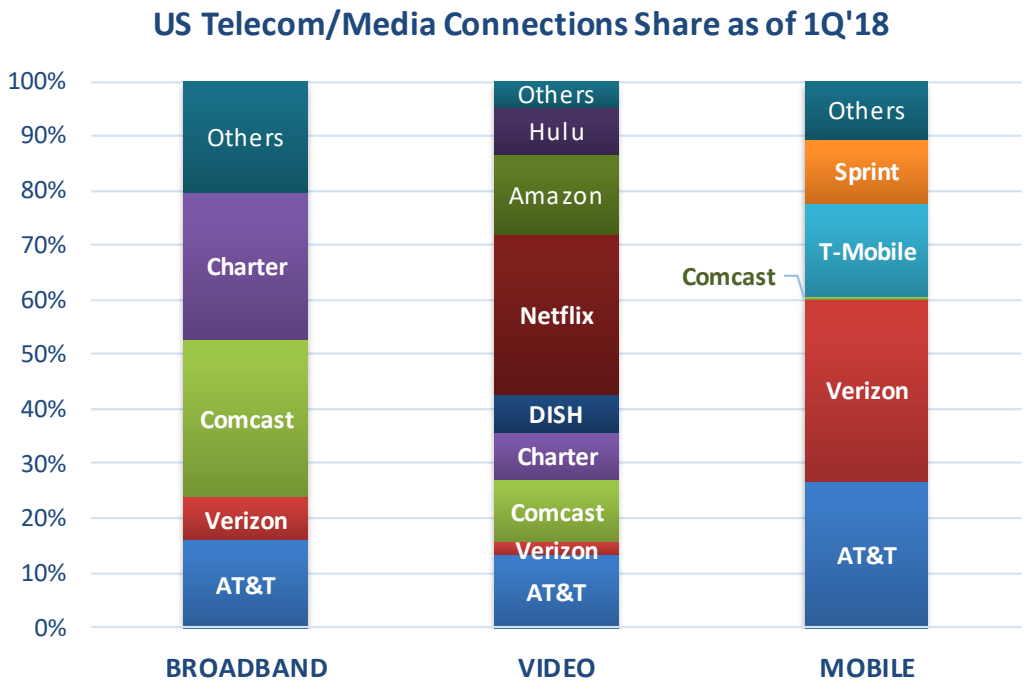
Source: Mobile Experts

Figure 11. OTT Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

Fixed vs. Mobile Competition for Subscribers and Spectrum Resources

As mobile and fixed operators pursue their respective wireless network strategies, it is interesting to contrast the differing motivations. With broad coverage in place with low-band LTE deployments, mobile operators are pursuing small cell densification projects to increase capacity in strategic hotspot locations. Meanwhile, fixed or cable operators are looking to "stitch" together various public hotspots that constitute their wireless network to provide a broader coverage. Mobile networks need capacity. Cable networks need coverage.

As the competition for consumer dollars for fixed and mobile broadband services increases, the operators from both camps appear to be heading towards intermodal competition (see figure below), indirectly competing for the unlicensed spectrum bands in those same strategic locations where consumers are likely to access broadband services.



Notes: 1) Broadband and Video connections are per household (possibly per individual in Video OTT case);
2) Mobile connections are per individual subscriber;
3) Video connections reflect facilities-based and OTT (Netflix, Amazon, and Hulu) subscriptions
4) Amazon reflects Prime Video 'watchers' out of the estimated 90M Prime members

Source: Mobile Experts

Figure 12. Fixed vs. Mobile Competition in the USA

Mobile operators are looking to harness the unlicensed bands using LTE-based technologies especially LAA to take advantage of existing LTE core infrastructure and operational simplicity. Cable operators have largely relied on inexpensive Wi-Fi infrastructure for their wireless access networks. If the cable operators look to pursue LTE-based technologies like the mobile operators, they will need to make investments in LTE core networks, which may not be trivial, but achievable – and likely necessary as they pursue mobile service opportunities.

The major cable operators in the USA have now entered the mobile business via MVNO. In kind, the major mobile operators are trialing 5G fixed wireless services as a possible response. As both cable and mobile operators increase their competitive intensity across respective core markets, the unlicensed band is expected to become an important battleground. Spectrum is a fundamental commodity in wireless business irrespective of whether it is licensed, unlicensed or shared. A key question for them is whether the unlicensed band can be utilized in a manner that provides traditional quality of service that end users expect.

3 TECHNOLOGY OPTIONS

The technology option for carrier unlicensed radio has expanded beyond the traditional IEEE 802.11 roadmap and Wi-Fi ecosystem and now includes LTE-based alternatives:

1) *License-Assisted Access (LAA)* – a 3GPP Release 13 standard that essentially formalizes LTE-Unlicensed (downlink carrier aggregation). Unlike LTE-U, fair coexistence with Wi-Fi in the unlicensed spectrum is handled by listen-before-talk (LBT) capability to ensure that channels are clear before transmission;
2) *Citizen Broadband Radio Service (CBRS)* – a three-tier licensing regime that allows operators to use 150MHz of the 3.5 GHz band in the U.S. on a shared basis. The CBRS channels can be aggregated along with a licensed anchor in LAA fashion or can run LTE-TDD on a standalone basis;
3) *MulteFire* -- running standalone LTE on unlicensed (or shared) spectrum without aggregating unlicensed carrier with a licensed carrier; and,
4) *LTE-WiFi Aggregation (LWA)* -- a 3GPP Release 13 standard that aggregates channel carriers at PDCP layer for downlink. LTE eNodeB base station decides which bearers (Wi-Fi and LTE) to use.

Meanwhile, the Wi-Fi based ecosystem of IEEE 802.11 technology roadmap in concert with commercialization efforts of the Wi-Fi Alliance continue to make great strides in advancing their cause:

1) *802.11 ax* – next-generation Wi-Fi technology that refreshes both the 2.4 GHz and 5 GHz bands with OFDMA and 8x8 MU-MIMO for better efficiency in dense environment;
2) *802.11 ad/ay* – 60 GHz WiGig technology providing multi-gigabit throughput in dense urban environments

802.11ac and 802.11ax (Wi-Fi Connectivity on 2.4 and 5 GHz)

The next-generation, 802.11ax, promises to greatly improve efficiency for high-density connectivity. In other words, it promises higher capacity and more connections in dense environments. The net performance improvement translates to 4x increase in capacity compared to 802.11ac and improved coverage. The higher efficiency is achieved from a few key features found in 802.11ax:

- 8x8 MU-MIMO on both the 2.4 and 5 GHz bands – increase capacity
- OFDMA – improves network efficiency and reduces latency
- Scheduled access
- WPA3 security

A comparison of technical feature sets between 802.11ac and 802.11ax is shown below.

	802.11ac	802.11ax
Frequency bands	5GHz	2.4GHz and 5GHz
Channel sizes	20, 40, 80, 160 MHz	20, 40, 80, 160 MHz
FFT sizes	64, 128, 256, 512	256, 512, 1024, 2048 (four times larger)
Subcarrier spacing	312.5KHz	78.125 kHz (four times narrower)
OFDM symbol duration	3.2 usec + 0.8/0.4 usec cyclic prefix	12.8 usec + 0.8/1.6/3.2 usec cyclic prefix (four times longer)
Modulation (highest)	256 QAM	1024 QAM
Data rates (peak)	433 Mbps (80MHz channel bandwidth, 1 spatial stream)	600 Mbps (80MHz channel bandwidth, 1 spatial stream)
	6.9 Gbps (160MHz channel bandwidth, 8 spatial streams)	9.6 Gbps (160MHz channel bandwidth, 8 spatial streams)

Source: Mobile Experts, National Instruments

Figure 13. Comparison of 802.11ac vs. 802.11ax

As noted above, 802.11ax operates in both 2.4 and 5GHz bands. More importantly, it significantly increases the number of subcarriers while preserving the existing channel bandwidth. Larger OFDM FFT sizes, narrower subcarrier spacing, and longer symbol time, in aggregate, improves robustness and efficiency while keeping the data rates the same as 802.11ac. In fact, with a higher modulation support for 1024 QAM, the 802.11ax provides a higher maximum data rate. More importantly though, it provides higher efficiency in multipath fading environments. With the higher number of subcarriers, the 802.11ax can more efficiently support simultaneous client devices by effectively divvying up the frequency.

Like 802.11ac, 802.11ax devices use explicit beamforming to direct data packets simultaneously to multiple users who are spatially separated. While the 802.11ac only defined MU-MIMO on the downlink, the 802.11ax standard defines uplink multiuser mode as well in which simultaneous data transmission from multiple client devices to an access point is possible. Another key addition of the 802.11ax standard is that it has defined two different ways of multiplexing users: Multiuser MIMO (MU-MIMO) and Multiuser Orthogonal Frequency Division Multiple Access (MU-OFDMA). In essence, 802.11ax borrows the underlying OFDMA technology used in LTE base stations to centrally manage multiple client devices, thus enabling more efficient access to a radio channel.

MU-MIMO operation in 802.11ax is essentially the same as the 802.11ac, in which an access point calculates a channel matrix for each user and steer simultaneous beams to different users with each beam containing specific packets for the intended client user. In 802.11ax, a maximum number of MU-MIMO transmissions has been increased from four to eight. For the uplink MU-MIMO, the access point initiates a simultaneous uplink transmission from each of the client devices by a trigger frame. In the case of multiple client devices responding in unison, the access point applies the channel matrix to the received beams and separates the information from each uplink beams.

In MU-OFDMA operation, specific sets of subcarriers can be allocated to different users over time. In fact, this is the same scheme that LTE uses in allocation of physical resource blocks for multiple users. Borrowing a similar LTE terminology, the 802.11ax defines the smallest subchannel as a Resource Unit (RU), with a minimum size of 26 subcarriers. As noted in the figure below, an access point can allocate the entire (20/40/80/160 MHz) channel to only one user at a time as is currently done in 802.11ac, or it can "chop up" the frequency (in RU) and allocate specific sets of RUs to different users over time.

Also, the resource scheduling in the uplink increases efficiency by moving away from contention-based resource allocation found in 802.11ac to scheduling approach (like LTE). With a combination of downlink and uplink MU-MIMO and MU-OFDMA, the 802.11ax is expected to support four times the average user throughput. With combinations of these techniques and higher physical data rates, 802.11ax is expected to improve user throughput and extend coverage with higher 8x8 MIMO, especially in dense environments, which has been an Achilles' Heel for Wi-Fi relative to LTE. Note that the MU-OFDMA and resource scheduling will improve contention between clients that share an access point, but not for users on different access points.

802.11 ad/ay (on 60 GHz)

The 60 GHz unlicensed technology widely known as 802.11ad WiGig has been around for many years. After the WiGig Alliance merged into the Wi-Fi Alliance back in early 2013, 802.11ad WiGig technology has been positioned as a "multi-gigabit Wi-Fi" technology for short-range applications such as wireless connectivity for VR headsets, HDMI/USB replacement, and so on. In the carrier space, 60 GHz 802.11 ad/ay solutions are sometimes found in short-range (100 meter) wireless backhaul applications.

The Facebook's Terragraph open-source project is the latest incarnation of ecosystem "builder" looking to rally other key companies to create fiber-replacement technology solution for multi-gigabit wireless connectivity solution for urban areas. Qualcomm is a major 60 GHz chipset supplier along with Intel and Peraso in this space. Qualcomm has already announced its pre-802.11ay chipset, and we are aware of many 60 GHz radio vendors looking to exploit the fixed wireless space with the 60 GHz point-to-multipoint radio solutions.

Source: Facebook Terragraph

Figure 14. Facebook Terragraph 60 GHz PtMP Network Architecture View

A key benefit of 60 GHz spectrum is the ultrawide channel – 2.16 GHz channel spacing! A whole lot can be transmitted in that amount of spectrum. Local regulatory bodies determine regional spectrum allocation from the total of six channels:

- USA: 57.0 – 71.0 GHz (6 channels available)
- Europe: 57.0 – 66.0 GHz (2 channels available)
- China: 59.0 – 64.0 GHz (2 channels available)
- S. Korea: 57.0 – 64.0 GHz (3 channels available)
- Japan: 57.0 – 66.0 GHz (4 channels available)
- Australia: 59.4 – 62.9 GHz (just shy of 2 channels available)

Due to the physical limits of RF propagation at the 60 GHz band, a range is fairly short – typically 200 meters in point-to-point wireless backhaul applications (although we have seen some vendors claiming even longer distances).

802.11ay is the next-generation 60 GHz technology that further extends the transmission speed and range. A draft 1.0 of the 802.11ay specification is expected to be released in the second half of 2017. According to the draft specification, the standard proposes to support 20-30 Gbps transmission rate and extend the range to 300-500 meters. These improvements are expected to be achieved through:

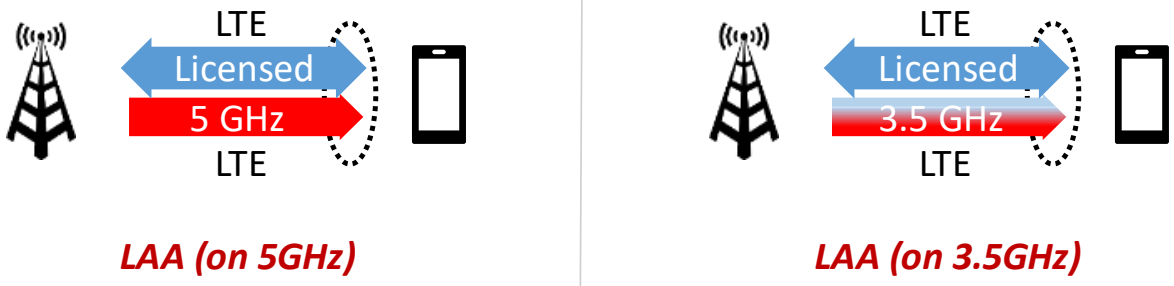
- Up to 4 channel bonding (each 802.11ad channel uses a maximum of 2.16 GHz bandwidth), yielding a maximum bandwidth of 8.64 GHz
- MIMO with a maximum of 4 spatial streams (a link rate per stream is 44 Gbps; thus with 4 streams, this can go up to 176 Gbps)
- High-order modulation scheme, possibly up to 256 QAM

With the tremendous amount of spectrum available in the 60 GHz unlicensed spectrum, 802.11 ad/ay solutions should find a home in many consumer and enterprise applications.

For the carrier space however, it will likely be used only for fixed wireless access and backhaul applications in dense urban environments. For the fixed wireless application, the CPE cost is a major determinant of viable business case. While the ecosystem is making great strides, we believe the market is still about 1-2 years out. The Terragraph ecosystem may provide enough scale and technology advancements to allow the 60 GHz point-to-multipoint market to flourish a bit sooner.

License-Assisted Access (LAA)

License Assisted Access (LAA) is built upon the carrier aggregation framework adopted in LTE Advanced (Release 10 through 13). Carrier aggregation combines more than one channel within the same band or with another band, effectively increasing the overall bandwidth available to a user equipment, thereby increasing bitrate. In the LAA framework, the unlicensed 5 GHz band is considered a secondary cell for downlink while the primary cell connection reserved for control signaling and uplink is anchored to a licensed band thus providing means to control service quality through control signaling on "guaranteed" licensed anchor carrier.



Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) Dotted ellipse represents that licensed/unlicensed/shared spectrum carriers are aggregated at the UE client device;

Source: Mobile Experts

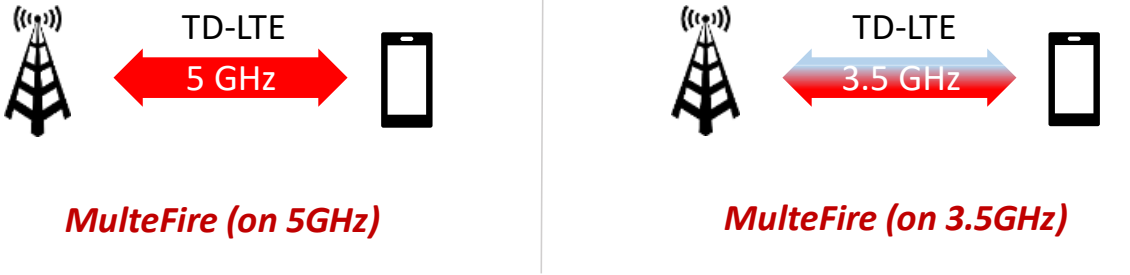
Figure 15. LAA Functional Overview

While the early head start that Verizon and T-Mobile were pushing for in the USA with LTE-Unlicensed (LTE-U) specification, a predecessor to LAA, did not materialize, the global scale of standardized LAA is expected to bring large scale as operators with limited spectrum view LAA as a path forward to opportunistically expand network capacity using cheap unlicensed spectrum.

MulteFire (on 3.5 GHz, 5 GHz, and Beyond)

Qualcomm, Nokia, Ericsson, and Intel formed the MulteFire Alliance to push for the unlicensed LTE technology that can be leveraged without a licensed spectrum anchor. In essence, MulteFire is an incarnation of LAA for those operators who do not have licensed spectrum for an "anchor" carrier for primary cell. Unlike LAA which precludes use by those who do not have licensed spectrum, MulteFire proposes to carry both control plane and data plane traffic entirely over unlicensed or shared band in a full TDD mode. Thus, it can be leveraged by enterprises, venue owners, and fixed providers.

Some view MulteFire as "CBRS for the rest of the world" outside of USA. It is still unclear today how much efficiency gain could be had with MulteFire over 802.11ax -- especially in light of the fact that 802.11ax tout 4x average user throughput improvement.[4] LTE standards allow for better coordination between cells than 802.11ax, but this is not proven in MulteFire field networks to date. In theory, the LTE ecosystem can be broadened to fixed operators or enterprises using the unlicensed spectrum.



Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) "Standalone" LTE via MulteFire can run on 5 GHz unlicensed spectrum as well as shared CBRS spectrum on PAL or GAA basis;
4) Multiple carriers on shared CBRS spectrum can be aggregated with licensed anchor carrier in LTE-U/LAA.

Source: Mobile Experts

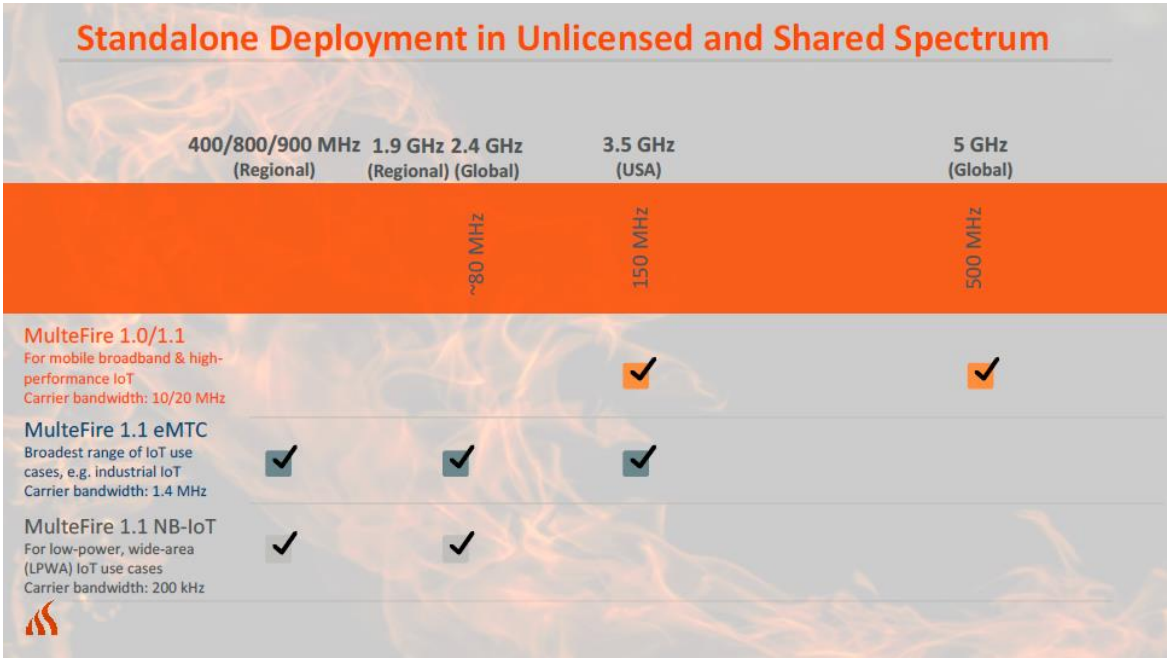
Figure 16. MulteFire Functional Overview

In practice, however, the adoption of MulteFire by the key target audiences, enterprises and operators, remains unclear. Enterprises have a large installed base of Wi-Fi systems and

[4] According to Qualcomm's MulteFire presentation dated May 24, 2016, MulteFire is expected to offer ~2x capacity gain over Wi-Fi (802.11ac). IEEE 802.11ax stated goal is to improve the average user throughput by 4x.

client devices. Though the neutral host and multi-operator aspects of MulteFire are clear demand drivers, whether the MulteFire ecosystem can achieve the competitive equipment pricing and scale of Wi-Fi remains unclear.

One likely area of market adoption of MulteFire may be in 3.5GHz CBRS deployments. Traditional mobile and Wi-Fi infrastructure vendors such as Nokia, Ericsson, Cisco, and Ruckus have joined the MulteFire Alliance. While we remain skeptical of its viability in the 5GHz band, we believe the benefits of MulteFire, namely neutral host support, private LTE applications in the "fresh" 3.5GHz CBRS band. In addition, it may provide a suitable solution for industrial IoT applications that require more deterministic service quality -- guarantees of performance will be more achievable with LTE than with Wi-Fi. As outlined in the MulteFire roadmap below, the ecosystem is expanding for IoT and Private LTE applications and expanding the specification to include other unlicensed spectrum bands as it monitors "5G Unlicensed" use case leveraging wider band possibly in the millimeter wave bands. According to the MulteFire Alliance, the MulteFire 1.1 specification is targeted for mid-2018, and is working towards Certification program.



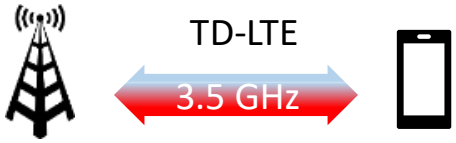
Source: MulteFire Alliance

Figure 17. MulteFire Roadmap Targets Mobile Broadband and IoT

CBRS (on 3.5 GHz)

In 2015, the U.S. Federal Communications Commission (FCC) formally established *Citizen Broadband Radio Service* (CBRS) for shared commercial use of the 3.5 GHz (3550-3700 MHz) band with the incumbent military radars and fixed satellite stations. For the first time, dynamic spectrum sharing rules have been defined to make additional spectrum available

for flexible wireless broadband use while ensuring interference protection and uninterrupted use by the incumbent users. The CBRS rule essentially allows mobile operation in TDD mode under coordinated sharing.



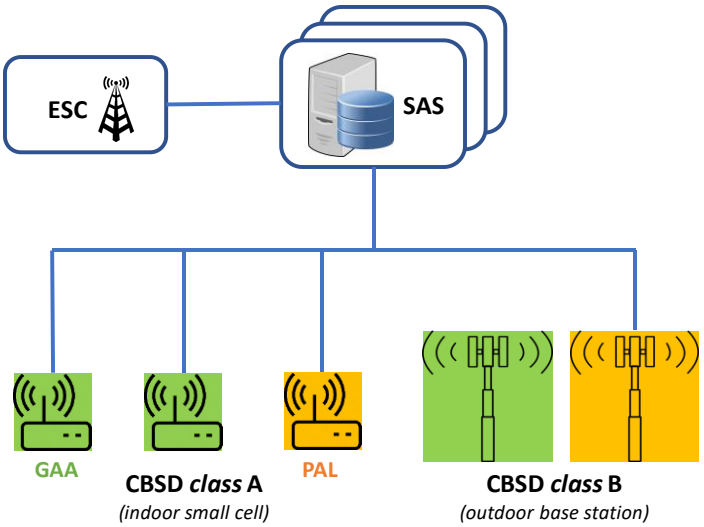
Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) "Standalone" LTE via MulteFire can run on 5 GHz unlicensed spectrum as well as shared CBRS spectrum on PAL or GAA basis;

Source: Mobile Experts

Figure 18. CBRS Functional Overview

Under the plan, a three-tier sharing paradigm coordinates spectrum access among the incumbent military radars and satellite ground stations and new commercial users. The three tiers are: *Incumbent*, *Priority Access License* (PAL), and *General Authorized Access* (GAA) users.

A key element of the CBRS spectrum sharing architecture is the *Spectrum Access System* (SAS). A SAS maintains a database of all CBRS base stations, formally referred to as *Citizens Broadband Radio Service Devices* (CBSDs), including their tier status, geographical location, and other pertinent information to coordinate channel assignments and manage potential interferences. To mitigate possible interference to tier 1 military radar systems, environmental sensors known as the *Environmental Sensing Capability* (ESC) are deployed in strategic locations near naval stations, mostly along coastal regions, to detect incumbent activities. When incumbent use is detected, the ESC alerts the SAS, which then directs CBSDs utilizing impacted CBRS channels in that area to move over to other channels. The cloud-based SAS enforces the three-tier spectrum sharing mechanism based on FCC rules via centralized, dynamic coordination of spectrum channel assignments across all CBRS base stations in a region.



Source: Mobile Experts

Figure 19. CBRS Functional Overview

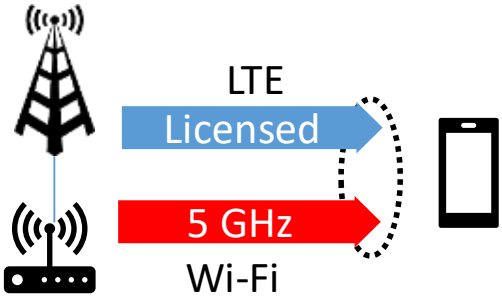
The CBRS rulemaking defines two classes of base stations: *class A* and *class B*. A class A base station can be thought of as indoor or low power outdoor small cells with a maximum conducted power of 24 dBm (per 10 MHz) and maximum EIRP of 30 dBm (1 watt). This type of small cell is similar to "enterprise-class" small cells in the marketplace with 250mW transmit power with a typical 2 dBi omni antenna or up to 6 dBi directional antenna. Meanwhile, a class B base station is meant for outdoor use with a maximum EIRP of 47 dBm (50 watts). With a very high-gain antenna, outdoor CBRS base station can potentially be used for fixed wireless purposes. While indoor and outdoor base stations can be assigned to either GAA or PAL, we expect to see more indoor GAA deployments until ESC certification and PAL auctions get finalized.

In the past year, the CBRS ecosystem was hampered by the delayed FCC certification of SAS. FCC certification of SAS is now expected by end of 2018. While there is still uncertainty around the final CBRS rules around spectrum license area size and term duration,[5] we expect CBRS radio deployments under GAA operation to start at the end of 2018 and possibly early 2019. While the expected ramp in 2018 has been delayed, Mobile Experts believes that CBRS network deployments will scale once the FCC provides clarity with a final ruling and PAL auction – likely in second half of 2019. Despite remaining uncertainties around final ruling and certification process at the government agencies, commercial rollout for fixed wireless and private LTE applications appears to be close at hand.

[5] CTIA and T-Mobile separately requested CBRS rule changes to FCC: http://www.fiercewireless.com/wireless/t-mobile-joins-ctia-pushing-fcc-to-reform-rules-for-3-5-ghz

LTE WLAN Aggregation (LWA)

LTE WLAN Aggregation (LWA) as defined in 3GPP release 13 provides a method to integrate LTE and Wi-Fi access network. LWA essentially aggregate or switch data traffic over LTE and Wi-Fi airlinks at radio access network layer – PDCP layer to be exact, just below the IP layer. In effect, end users would experience a capacity boost from utilizing Wi-Fi network as if they were using LTE. One of the drawbacks of LWA is that the link aggregation only works on the downlink only and does require changes to WLAN access point infrastructure. Perhaps due to these drawbacks, we have not observed much market traction of this method in commercial deployments beyond limited commercial launch in Taiwan and Singapore.



Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) Dotted ellipse represents that licensed/unlicensed/shared spectrum carriers are aggregated at the UE client device;

Source: Mobile Experts

Figure 20. LWA Functional Overview

4 OVERALL CARRIER "UNLICENSED" RADIO OUTLOOK

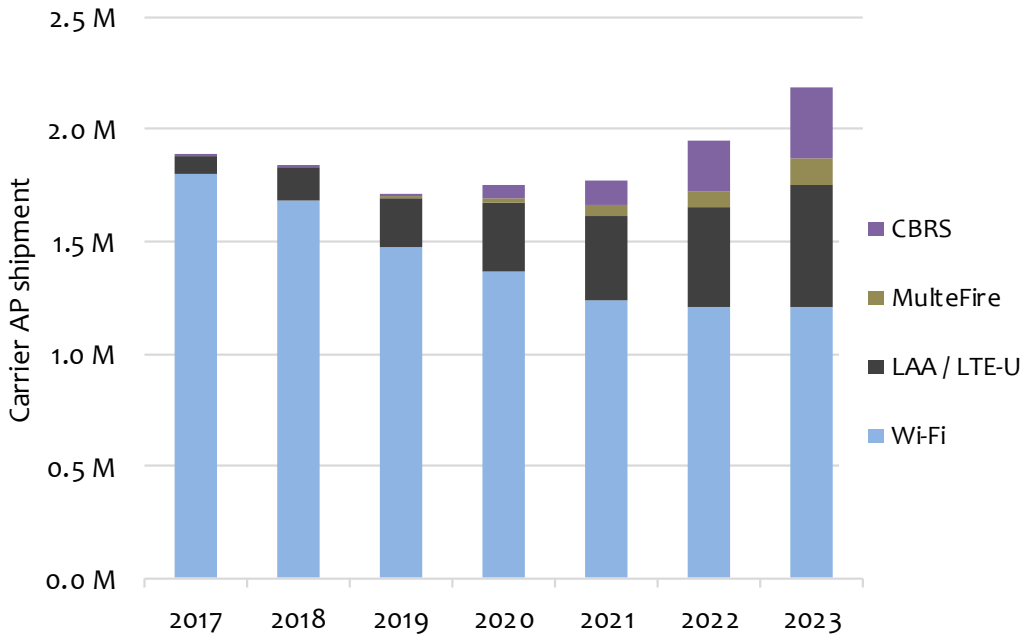
The carrier "unlicensed" wireless infrastructure market using Wi-Fi and LTE-based technologies is expected to grow as operators have expanding technology options to more efficiently leverage the unlicensed and shared spectrum bands. Mobile operators with limited licensed spectrum holdings can now expand capacity through carrier aggregation via LAA or CBRS instead of Wi-Fi offload or a link aggregation across disparate radio technologies. Cable operators can continue to leverage Wi-Fi for wireless extension of core broadband services and potentially leverage LTE in CBRS band for mobile services. Meanwhile, OTT service providers such as wireless ISPs can leverage both Wi-Fi and LTE-based technologies for fixed wireless services. The expanding choice of Wi-Fi and LTE technologies for the unlicensed and shared spectrum bands will increase the overall carrier unlicensed radio market as the new technologies will open new market opportunities for different types of service providers.

As noted previously, in this report, a carrier "unlicensed" radio node can be deployed as a standalone access point (AP) or integrated into a customer premise equipment (CPE) for broadband at home or business. For example, a standalone AP can be mounted on lampposts for public hotspot coverage or on a tower or rooftop for fixed wireless services. In addition, carriers typically integrate Wi-Fi onto CPEs to extend broadband connectivity service to increasing number of wireless devices at homes and businesses.

Carrier Unlicensed Radio Shipment Forecast

As the mobile industry recalibrates its unlicensed spectrum strategy away from Wi-Fi offload to Carrier Aggregation across licensed and unlicensed bands with LAA for "Gigabit LTE" services[6], Mobile Experts forecasts a dip in the overall carrier standalone AP shipments in the near term. The early days of huge Carrier Wi-Fi deployments by the mobile operators for data offload are long gone. While the wireline telco and cable operators will continue to deploy Wi-Fi infrastructure for public hotspot coverage at select venues and business locations, the mobile operators' mass deployment of carrier Wi-Fi infrastructure will be limited going forward. As a result, the overall carrier "unlicensed" radio node shipment will decline in the near term before picking it back up in 2020.

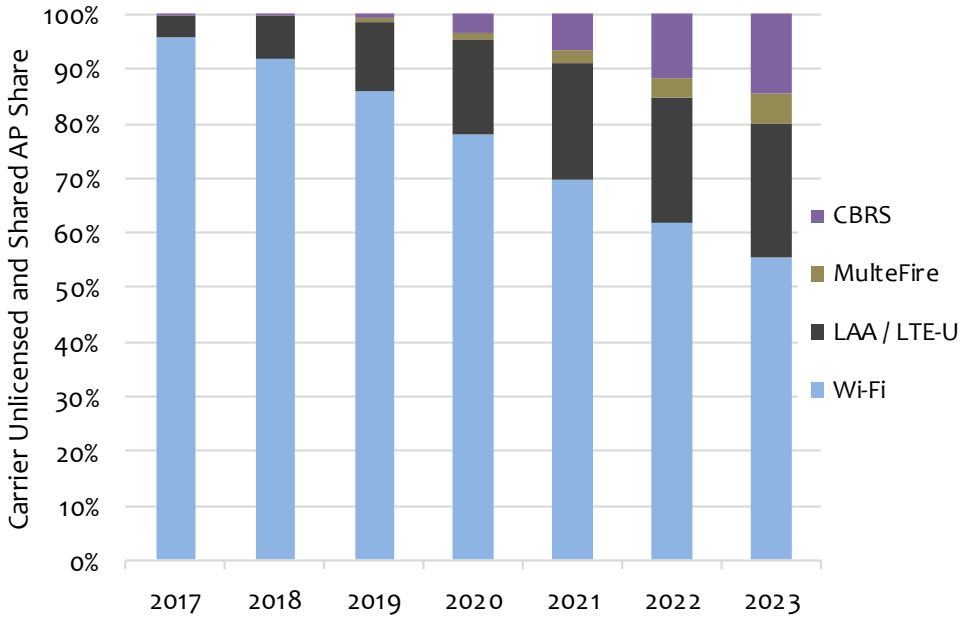
[6] With Carrier Aggregation of both licensed and unlicensed spectrum bands with LAA, 256 QAM, and 4x4 MIMO, LTE peak throughput can reach 1Gbps downlink. While corresponding higher category UE client devices are needed, operators will undoubtedly market "Gigabit LTE" services.



Source: Mobile Experts

Chart 2: Carrier Unlicensed AP Shipment Forecast, 2017-2023

While we expect the use of LAA multiband small cells to pick up and eventually overtake the role of Carrier Wi-Fi in many of the outdoor and mobile-related applications, the pace of LAA and other LTE-based AP deployments will be slower than the decline in Carrier Wi-Fi in the beginning of our forecast period. Even with the near-term decline with the "Wi-Fi to LAA" transition, Mobile Experts forecasts the carrier unlicensed AP market to realign for new growth. After the "transition," we forecast the Carrier unlicensed AP market to grow at roughly 8% annually, as the different operator groups take advantage of both Wi-Fi and LTE based technologies that take advantage of unlicensed and shared spectrum bands.



Source: Mobile Experts

Chart 3: Carrier Unlicensed AP Technology Share, 2017-2023

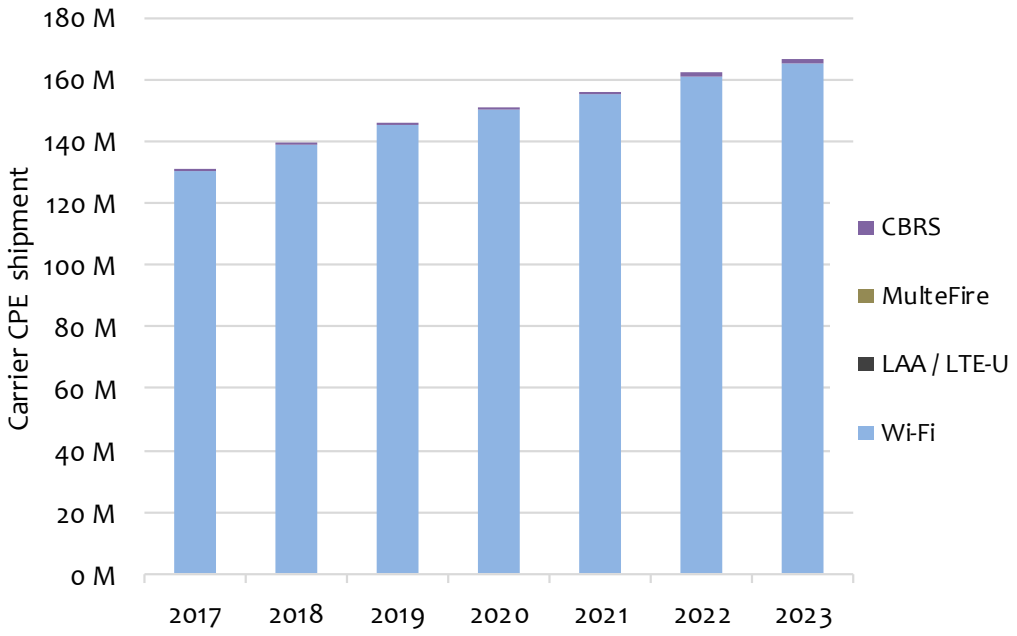
With forecasted rapid adoption of LTE-based unlicensed ("LTE-unlicensed") technologies (i.e., LAA, CBRS, and MulteFire) especially by the mobile operators, the cumulative LTE-unlicensed share of the overall Carrier wireless AP infrastructure market is forecasted to reach from just 4% in 2017 to 45% by 2023. With the LAA field trials bearing successful headline throughput numbers, Mobile Experts believes that a significant worldwide deployment to occur in 2019-2020 timeframe as the operators tout "Gigabit LTE" speeds.

Customer Premise Equipment (CPE) as Carrier Unlicensed Radios

While the headlines for carrier wireless infrastructure deployments in unlicensed spectrum is often dominated by Carrier Wi-Fi public hotspot deployments at parks, stadiums or train stations, a bulk of the unit shipments comes from Broadband CPEs. (Note that we define a "Broadband CPE" as a customer-premises box that acts as an AP for the operator). With hundreds of millions of broadband connections, some carriers are increasingly integrating wireless radios onto CPEs to extend broadband and video services at homes and businesses, and also to enhance "inside-out" wireless coverage for "nomadic" service. For example, tens of millions of "hotspots" that some carriers tout are mostly residential broadband CPE "homespots."

While it is not a core focus of this report, Mobile Experts believes that the entire carrier broadband CPE market in hundreds of millions of units, including residential segment, can be a big foundation for a future growth of the Carrier Unlicensed Radio market if carriers focus on the "inside-out" strategy as a key aspect of mobile services. With performance improvements across both the 2.4 GHz and 5 GHz bands, we expect the carriers to quickly

transition to 802.11ax Wi-Fi. While Wi-Fi will remain the dominant choice for carriers' wireless strategy at home, growing from over 130M in 2017 to over 165M units in 2023, we forecast some broadband CPEs to embed CBRS radios to provide "inside out" mobile coverage for cable operators in the USA.



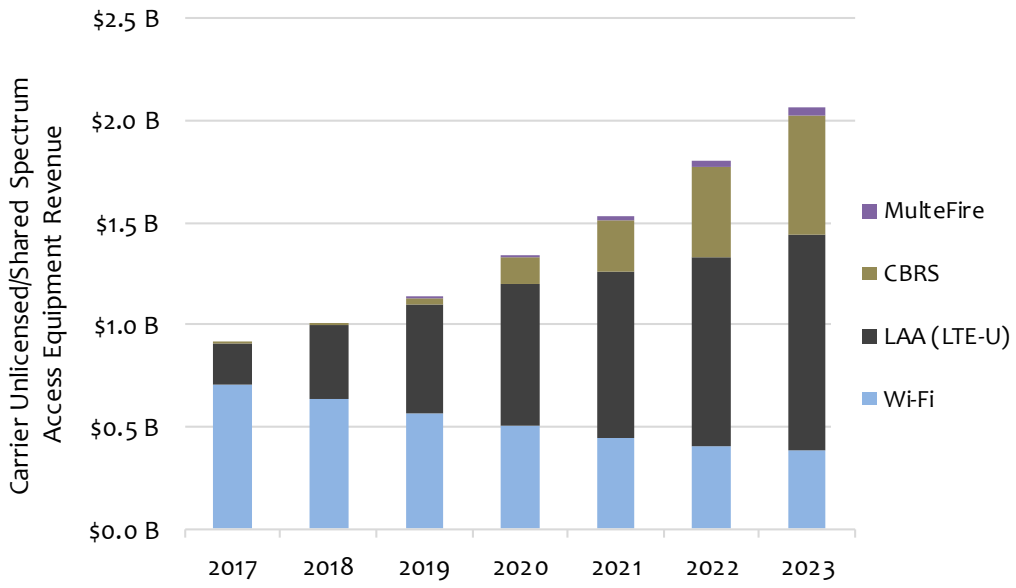
Note: Only captures Wi-Fi integrated broadband CPEs; Excludes video set-top CPEs

Source: Mobile Experts

Chart 4: Carrier Wireless Broadband CPE Shipment Forecast, 2017-2023

Carrier Unlicensed Radio Revenue Forecast

While the shipments of unlicensed radios are dominated by Wi-Fi, the revenue impact of LAA and CBRS is much more noticeable – as they are higher-priced carrier units. LAA multiband small cells and CBRS standalone radios command higher average selling prices than "enterprise-class" Wi-Fi access points used in carrier applications. Mobile Experts expects the LAA and CBRS infrastructure units to generate over $1.6 billion in 2023 – a significant jump from less than $200M in 2017. Meanwhile, the Carrier Wi-Fi infrastructure market, comprised of APs and select business CPEs used for mobile is forecasted to decline from $700M in 2017 to less than $400M in 2023. The impact of MulteFire on the carrier wireless infrastructure market is expected to be *de minimus* based on enterprise-centric applications such as private LTE and IoT that MulteFire targets.

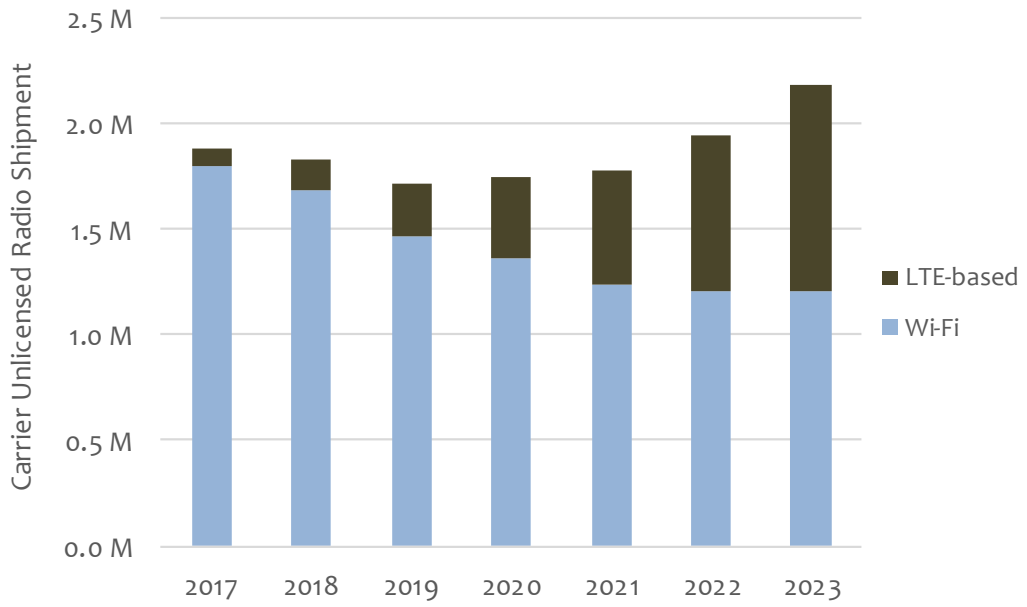


Source: Mobile Experts

Chart 5: Overall Carrier Unlicensed Access Equipment Revenue Forecast, 2017-2023

Carrier Unlicensed Radio - Wi-Fi vs. LTE Outlook

The overall carrier unlicensed wireless infrastructure market made up of standalone access points (APs) is expected to grow to about 2.2M units by 2023 with Wi-Fi representing the bulk of the Carrier Unlicensed Radio AP units. We are forecasting a healthy growth of LTE-based unlicensed technology (i.e., LAA, CBRS, and MulteFire) adoption on standalone APs – just under 1M units in 2023.

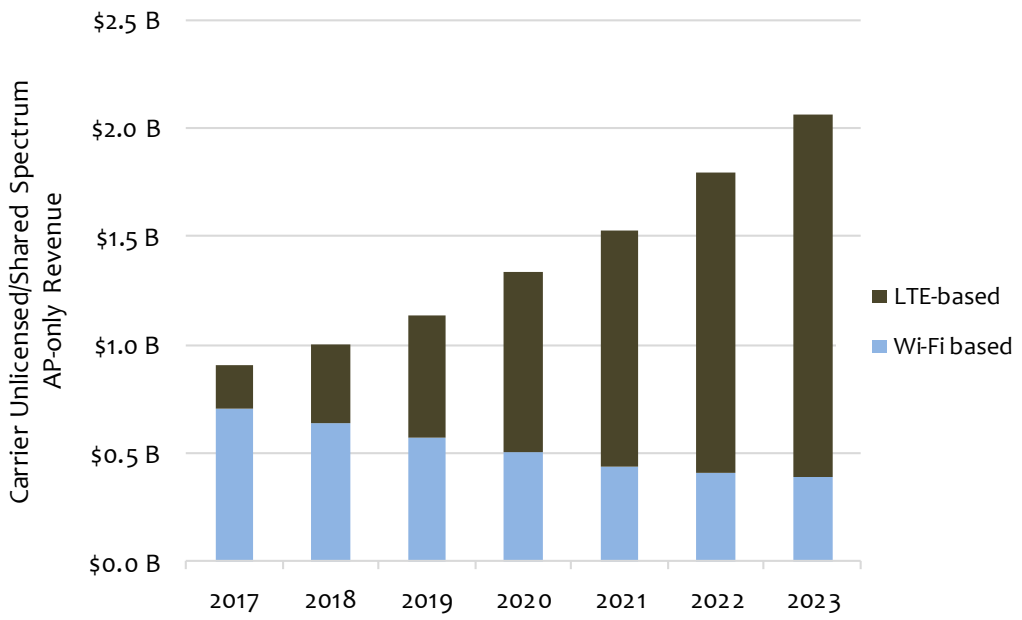


Note: Only captures Wi-Fi integrated broadband CPEs; Excludes video set-top CPEs

Source: Mobile Experts

Chart 6: Carrier Unlicensed Radio Shipment Forecast, Wi-Fi vs. LTE, 2017-2023

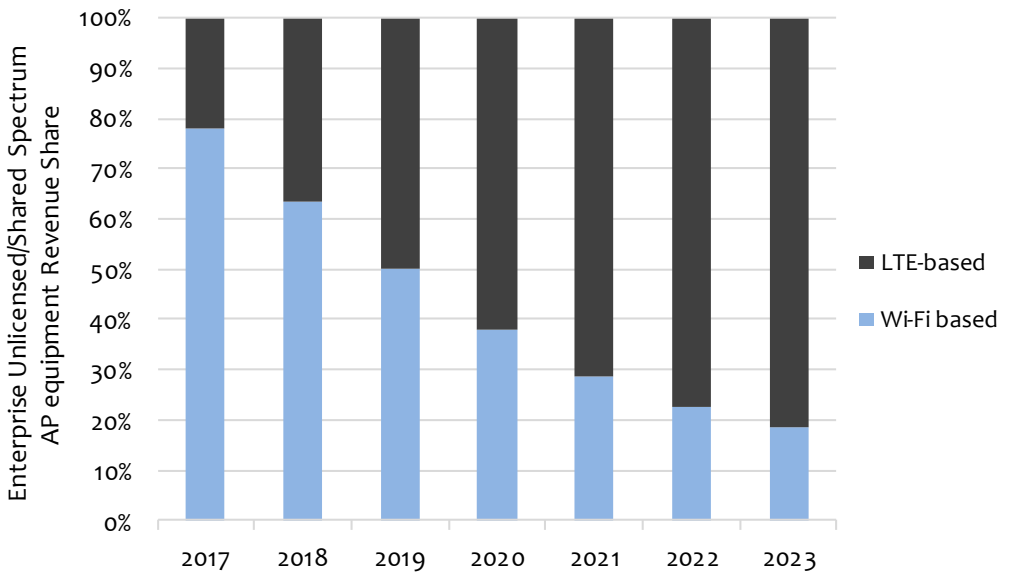
The "LTE-unlicensed" technologies including LAA, CBRS, and MulteFire target different use cases from mobility to fixed wireless that will require high-value access points. Mobile operators are favorable towards LAA and CBRS for mobile densification to augment network capacity with unlicensed and the additional shared spectrum in the 3.5 GHz band. Meanwhile, the U.S. cable operators appear to be leaning towards CBRS for mobile and Wi-Fi for indoor broadband connectivity. Market adoption of "LTE-based" technologies are expected to quickly increase over time as the different operator groups start to leverage the technologies for both mobile and nomadic applications. Mobile Experts forecasts this group of LTE-based technologies to represent over $1.6 billion in Carrier Unlicensed Radio infrastructure equipment revenue by 2023. With higher unit volume shipment, but lower average selling price, the Carrier Wi-Fi equipment market is expected to decline to about $400M in 2023 as the majority of mobile operator spend on "unlicensed" infrastructure moves to LAA and CBRS.



Source: Mobile Experts

Chart 7: Carrier Unlicensed Radio Equipment Revenue Forecast, Wi-Fi vs. LTE, 2017-2023

The LTE-based Carrier Unlicensed Radio infrastructure equipment is expected to increase market share capture of the overall Carrier Unlicensed Radio equipment market – growing from just over 20% in 2017 to over 80% in 2023. market representing over $9B by 2023. That is a meaningful impact when one considers that the LTE-based access market represents only 2% of the total carrier unlicensed radio equipment revenue in 2017. Meanwhile, the Carrier Wi-Fi equipment market is expected to hover around $400M - $600M during that period.

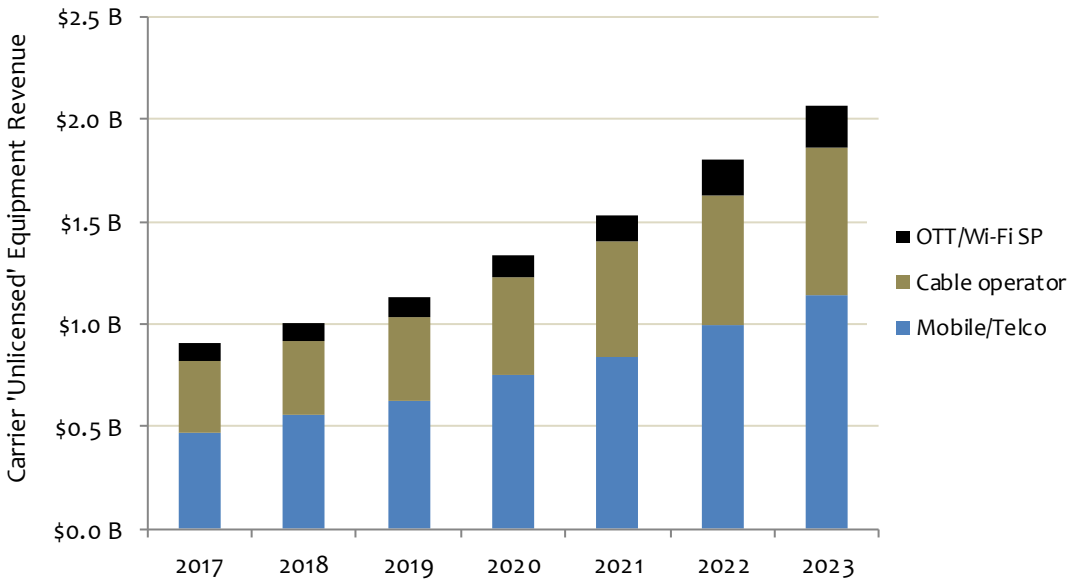


Source: Mobile Experts

Chart 8: Carrier Unlicensed Radio Equipment Revenue Share, Wi-Fi vs. LTE, 2017-2023

Carrier Unlicensed Radio Outlook by Operator Type

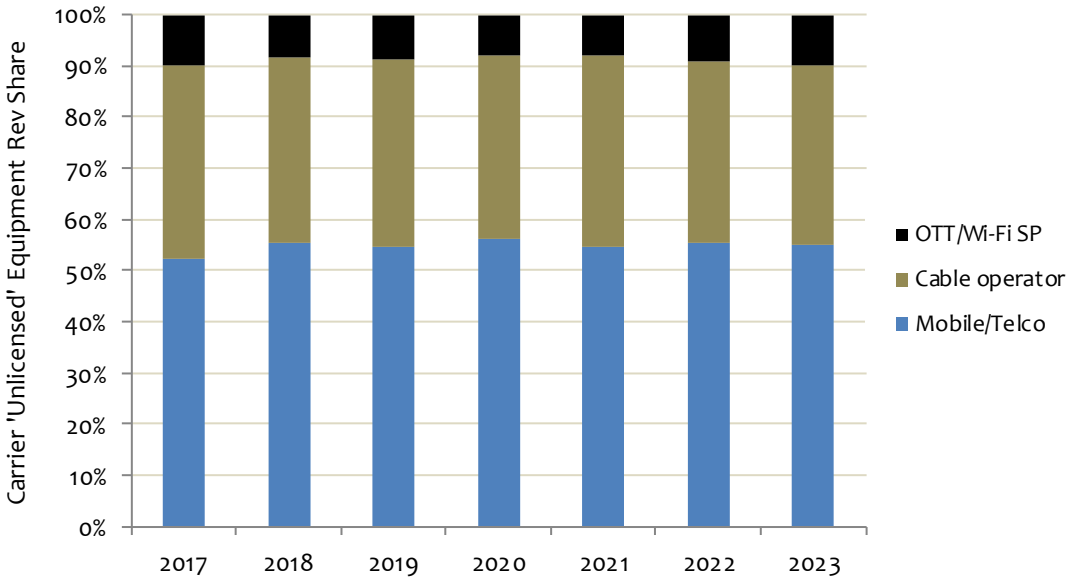
Including hundreds of millions of Wi-Fi integrated broadband CPEs that are shipped each year, the carrier wireless infrastructure market comprised of access points and CPEs is heavily influenced by fixed broadband operators. Globally, the fixed broadband services are dominated by incumbent telcos, who are also the mobile operators in most countries. Because of this, the mobile/telco operators represent the biggest purchasers of carrier unlicensed wireless infrastructure equipment such as Carrier Wi-Fi and Wi-Fi integrated broadband CPEs. Cumulatively across Wi-Fi, LAA, CBRS, and MulteFire infrastructure equipment, the mobile/telco operators represent the largest market, followed by the cable operators, then the OTT/WiFi operators. This is not surprising since the respective operator groups hold varying degrees of fixed and mobile broadband service footprints. The larger the service footprint, more carrier wireless infrastructure equipment (in the form of APs and CPEs) are needed to service the subscribers.



Source: Mobile Experts

Chart 9: Carrier Unlicensed Radio AP Equipment Revenue by Operator Segment, 2017-2023

With faster growth of broadband CPEs equipment into homes and businesses, the carrier "unlicensed" infrastructure equipment market to the cable operators is expected to grow faster than the mobile/telco operators. However, the size of the market opportunity to the mobile operators is expected to be larger – about 50-60% of the overall market during our forecast period.

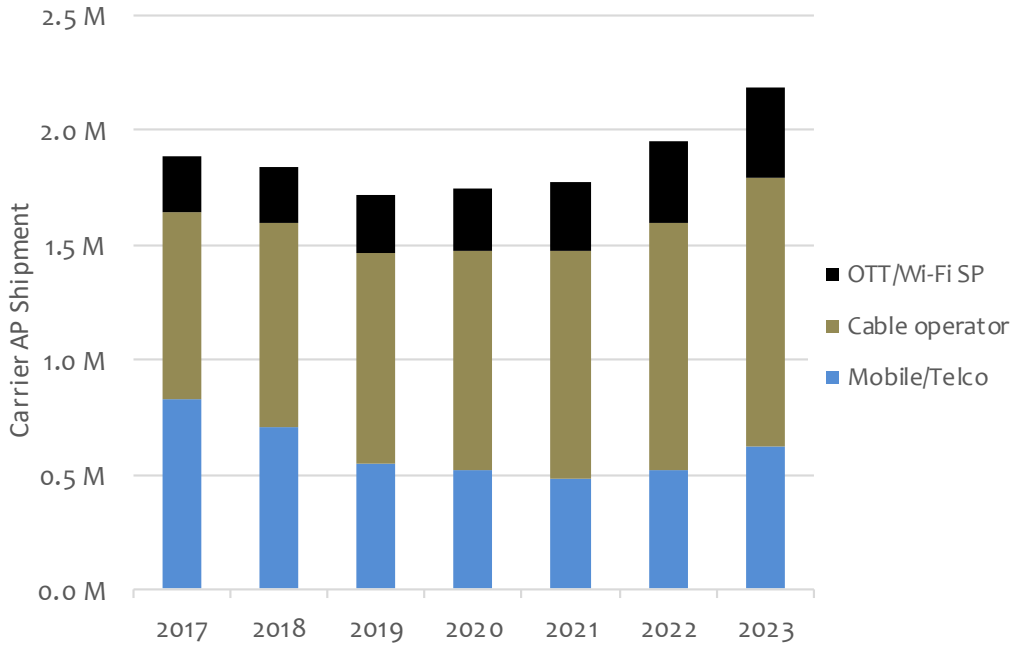


Source: Mobile Experts

Chart 10: Carrier Unlicensed Radio Equipment Rev Share by Operator Segment, 2017-2023

Some mobile operators are keen to opportunistically aggregate carriers across licensed, unlicensed and shared spectrum bands to increase network capacity and offer higher-speed user throughput to subscribers with latest UE Category smartphones that support Carrier Aggregation and LAA. For operators with limited spectrum holdings, LAA small cells in concert with latest smartphones offer a good pathway toward "Gigabit LTE" and 5G services. Some of the mobile operators' increasing capital expenditures towards small cells are expected to encompass LAA and CBRS multiband units.

The U.S. cable operators are eager to harness the 3.5 GHz CBRS spectrum for mobile use in the near future. In addition to continued investments in outdoor and indoor Carrier Wi-Fi infrastructure to aid in fixed broadband and MVNO mobile services, the 150 MHz of CBRS spectrum and a broad ecosystem of CBRS partners presents a good opportunity for the cable operators to stand up LTE-based mobile network, in addition to Wi-Fi footprint inside homes and businesses.



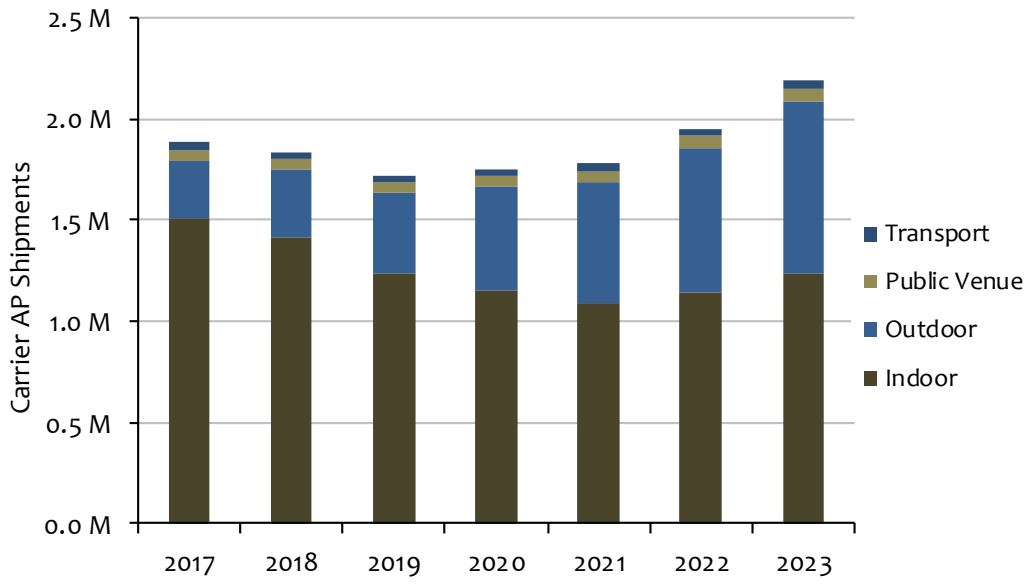
Source: Mobile Experts

Chart 11: Carrier Unlicensed AP Shipment Forecast by Service Provider, 2017-2023

With broader technology choices including LTE use in unlicensed spectrum using LAA, the mobile operator group is expected to be a large constituent of LAA small cells. With the delay in CBRS launch, the share of carrier unlicensed AP shipment to the cable operator group has been reduced from our previous forecast; however, we still expect the cable operators to be active in deployment of CBRS access points and via CPEs. Meanwhile, we expect sizable shipments to the OTT service provider segment, especially for CBRS neutral host and private LTE applications. We expect the OTT operators to leverage both Wi-Fi based and LTE technologies.

Carrier Unlicensed Radio Indoor/Outdoor Deployment

Carrier Unlicensed Radios are predominantly deployed indoors via wireless broadband CPEs or standalone indoor access points at key locations to provide nomadic access or mobile data offload to host or partner service providers. While there is a meaningful base of public outdoor deployments in key "hotspot" locations like parks, public buildings, etc., most of near-term outdoor shipments will come from system upgrades as there are fewer strategic locations for expensive outdoor installations. In the mid and longer term, we expect the outdoor installations to increase as the mobile operators leverage LAA outdoor small cells, in conjunction with indoor units, to densify their networks towards "Gigabit LTE" services. Carrier Wi-Fi deployments at key public venues like stadiums and airports will continue especially in context of IoT applications which will be enhanced with 802.11ax upgrades. Moreover, "transport" applications like mobile hotspots, train and airplane Wi-Fi services will drive Carrier Wi-Fi deployments in those verticals.



Note: Only captures Wi-Fi integrated broadband CPEs; Excludes video set-top CPEs

Source: Mobile Experts

Chart 12: Carrier & Enterprise Unlicensed Radio Shipment, by Market Segment, 2017-2023

5 CARRIER WI-FI OUTLOOK

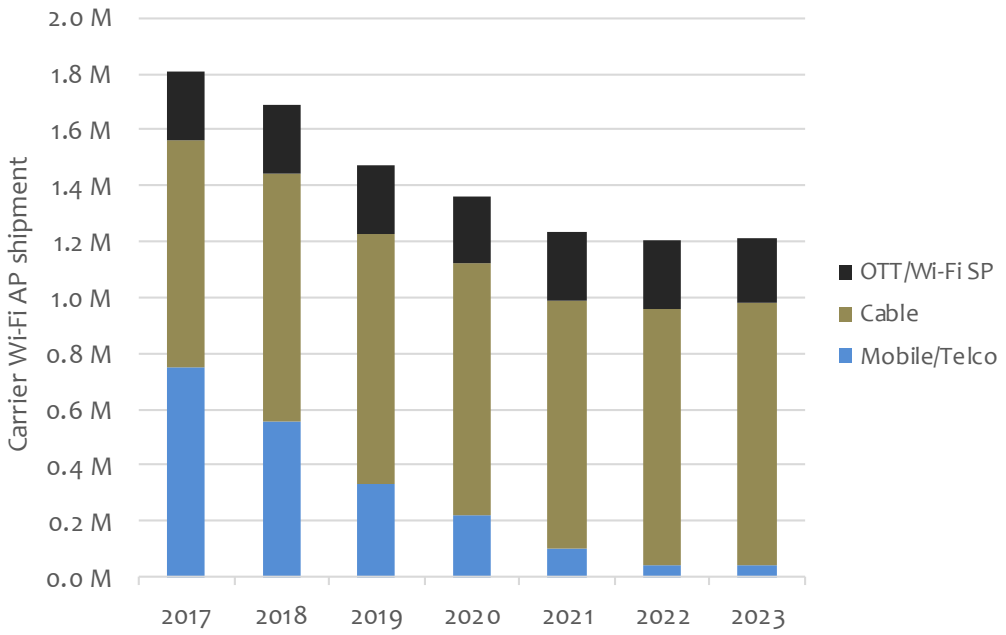
Unlicensed spectrum--especially the 2.4 GHz and 5 GHz bands--remain the realm of Wi-Fi technologies, primarily for enterprise wireless local area networking (WLAN) services and carrier services at home and small businesses via Wi-Fi integrated broadband gateway or modems. The Carrier Wi-Fi equipment market can be segmented into two broad segments: standalone access point (AP) for indoor and outdoor and customer premise equipment (CPE, often referred to as 'homespots') for indoor applications. As noted in the beginning, in this report, we define the Carrier Unlicensed Radio infrastructure market as AP and select business-class CPE market dedicated for mobile and nomadic applications.

Carrier Wi-Fi standalone access point (AP) shipments are forecasted to wind down as more amenable LTE-centric technologies for unlicensed spectrum use such as LAA and CBRS (on shared spectrum band) are now available for the mobile operators. The mobile operator adoption of Carrier Wi-Fi standalone infrastructure is forecasted to decline quickly as their reliance on disparate Wi-Fi network for data offload can be more elegantly handled[7] through LTE and 5G unlicensed technologies such as LAA, eLAA, and 5G unlicensed standard work in progress. While system upgrades and public Wi-Fi hotspot deployments will sustain Carrier Wi-Fi standalone AP shipment in the near-to-mid term, we expect mobile operators to mainly focus on LTE and 5G based infrastructure for the unlicensed and shared spectrum use going forward.

Meanwhile, the cable operators will continue to leverage Wi-Fi in the unlicensed spectrum bands for outdoor hotspot deployments to complement their fixed broadband services and leverage for its growing mobile wireless strategy with MVNO. Mobile Experts forecasts consistent annual shipments of 70,000 to 100,000 standalone APs to complement millions of Wi-Fi integrated broadband CPEs for mobile data offload strategy.

Finally, the other over-the-top service providers like wireless ISPs (WISPs) will continue to rely on Wi-Fi based AP infrastructure for data offload and location-based services. Excluding the mobile operators, carriers will continue to look to Wi-Fi technology to harness the unlicensed spectrum bands especially as possible new spectrum in the 6GHz band and 60 GHz product solutions become more widely available.

[7] Running LTE on unlicensed and shared bands and utilizing Carrier Aggregation to bond multiple carrier channels afford a straightforward means to increase capacity while maintaining service quality through deterministic control signaling on exclusive licensed spectrum.

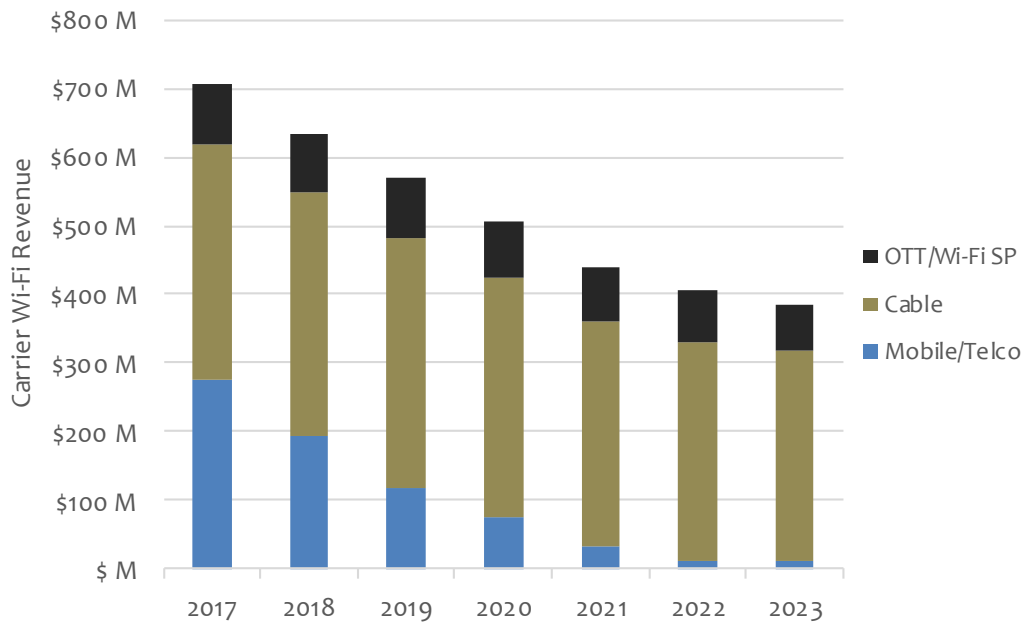


Source: Mobile Experts

Chart 13: Carrier Wi-Fi (standalone) AP Shipment Forecast by Operator Segment, 2017-2023

Carrier Wi-Fi Revenue Forecast

Looking at individual "unlicensed" technology adoption trends of the operator groups, one can observe the varying degrees of activism by the different operator groups. Looking at the Carrier Wi-Fi segment individually, we expect the market activity among the fixed-line telco, cable and Wi-Fi centric OTT service providers to be fairly stable. Meanwhile, we expect the mobile operators to drastically cut their Carrier Wi-Fi spending now that they have LTE-based solutions to take advantage of unlicensed and shared spectrum. It should be noted that telcos in many regions are also mobile operators. The telco side of these "converged" operators will continue to sustain their Carrier Wi-Fi spend especially CPE-based Wi-Fi gears. In summary, the Carrier Wi-Fi market trends will remain "business as usual" for wireline operators, but the mobile operators will turn their CapEx spend towards LTE-based unlicensed equipment especially LAA and CBRS.



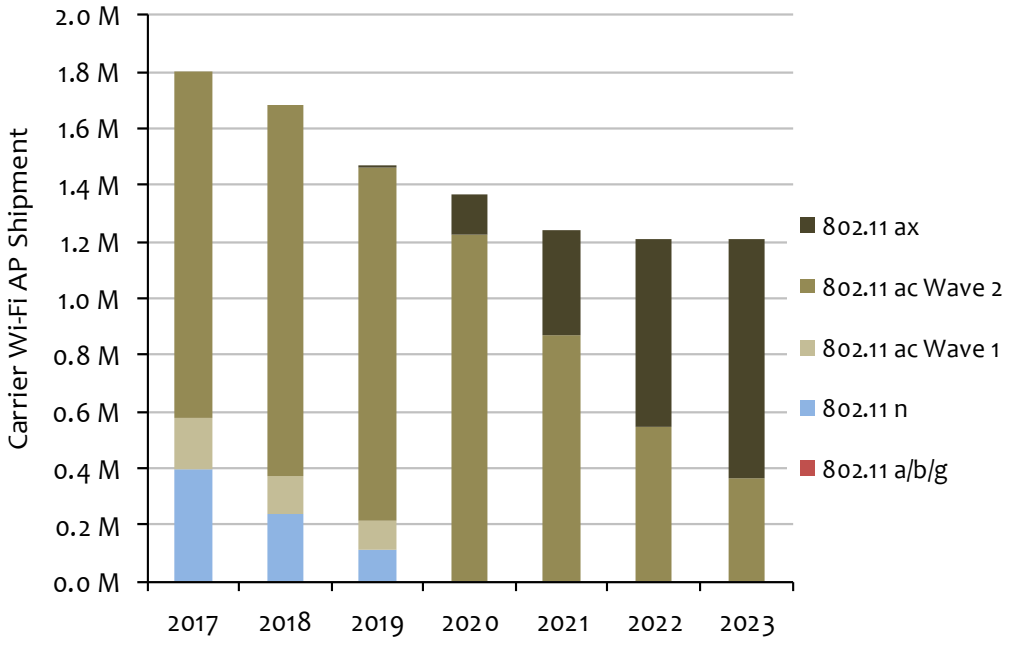
Source: Mobile Experts

Chart 14: Carrier Wi-Fi Equipment Revenue by Operator Segment, 2017-2023

Carrier Wi-Fi 802.11 Technology Transition

The IEEE 802.11 technology transition in the Carrier Wi-Fi segment had historically trailed that of the Retail or Enterprise WLAN market segments. Generally, the Retail/SOHO and Enterprise markets adopt newer 802.11 technology, followed by the Service Provider or Carrier segment. While the IEEE 802.11ax draft approval has been delayed, we still expect 802.11ax enterprise WLAN products to hit the market in second half of 2019, with adoption in handsets throughout 2020 and beyond. The Carrier Wi-Fi products supporting 802.11ax to hit the market in 2020 and go 'mainstream' thereafter.

To take advantage of OFDMA and 8x8 MIMO features that provide performance improvements including "scheduled access" benefits, we expect some operators to adopt 802.11ax faster than historical trends. For example, Comcast is already deploying 8x8 MIMO feature on its 802.11ac Wi-Fi integrated CPE products as a part of its xFi service launch. While the Comcast's xFi CPE is not officially 802.11ax, the core feature of 8x8 MU-MIMO feature provides the benefits early on while the Wi-Fi chipset ecosystem works towards commercializing the official 802.11ax products to the market.

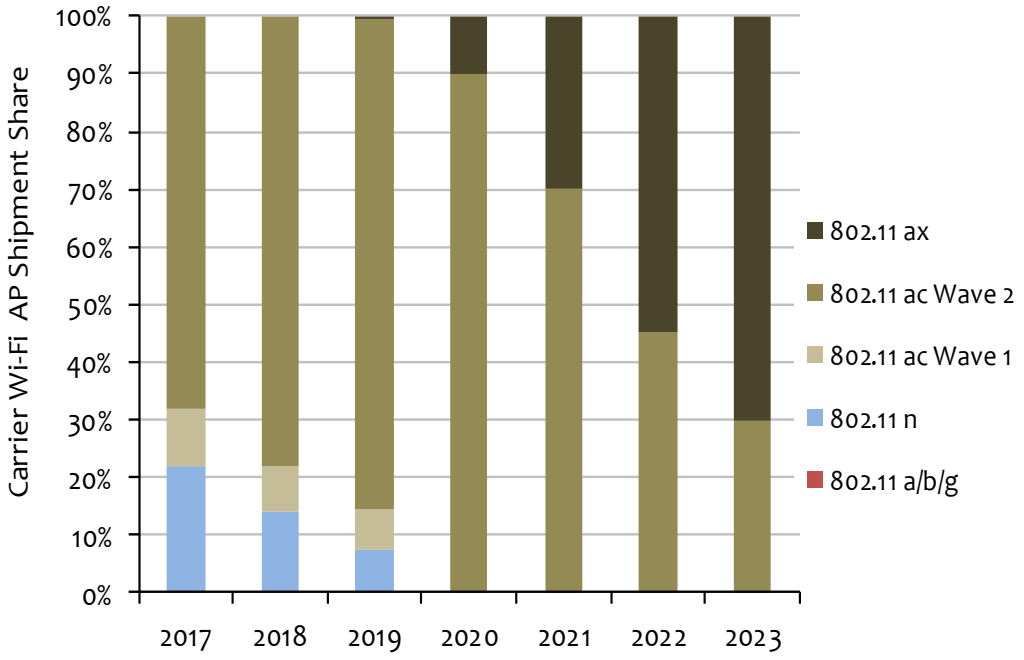


Note: Only captures Wi-Fi integrated broadband CPEs; Excludes video set-top CPEs

Source: Mobile Experts

Chart 15: Carrier Wi-Fi 802.11 Technology Transition, Wireless Access Market, 2017-2023

While the 802.11ac wave2 remains the dominant Wi-Fi technology embedded in Carrier Wi-Fi products today, Mobile Experts forecasts 802.11ax to overtake the previous generation in 2022.



Source: Mobile Experts

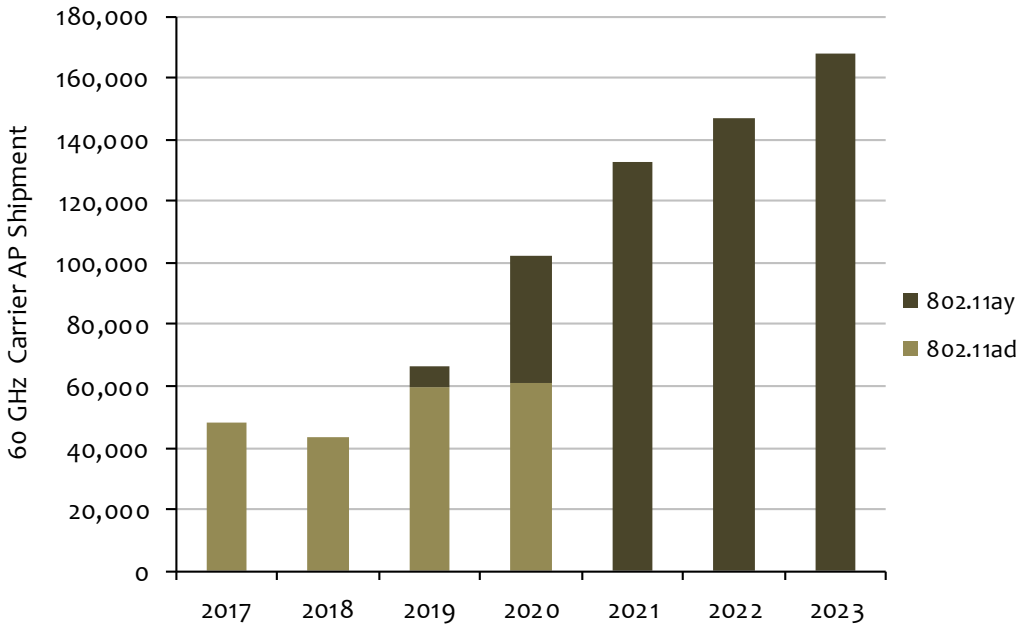
Chart 16: Carrier Wi-Fi 802.11 Technology Share, Wireless Access Market, 2017-2023

Carrier Wi-Fi 60 GHz (802.11 ad/ay) Outlook

Unlicensed spectrum access at 60 GHz through 802.11ad (WiGig) and eventually 802.11ay promises many interesting applications spanning across consumer electronics and carrier services including VR headsets, HDMI/USB replacement, campus backhaul to name a few. In the context of Carrier Wi-Fi application, we believe point-to-point and point-to-multipoint fixed wireless access provide interesting near-term opportunities.

While OTT wireless service providers who lack owned network infrastructure may look to the huge bandwidth available in the 60 GHz millimeter wave band for multi-Gbps backhaul, we believe traditional cable and mobile carriers will primarily look to their owned wireline infrastructure for backhaul. For dense urban wireless deployments for over-the-top service providers with limited owned infrastructure, Mobile Experts believes that 60 GHz access can be a good alternative solution for short-range (less than 1000 feet) high-capacity backhaul, or even fixed wireless access. With the IEEE task group expected to complete the 802.11ay specification draft in 2019, Mobile Experts expects the 802.11ay equipment ramp to happen in 2020. With higher capacity and greater range (about 1000 feet) with channel bonding and MIMO features, Mobile Experts believes the market opportunity will certainly grow for the 802.11ay adoption if the Terragraph ecosystem matures to bring the fixed wireless CPE costs down to sub-$100.

Note that we don't count the 60 GHz Wi-Fi in our main forecast for wireless access, since we don't expect any operators to deploy 60 GHz infrastructure for general access. This technology will be used for backhaul and for fixed wireless access, not for mobile broadband.

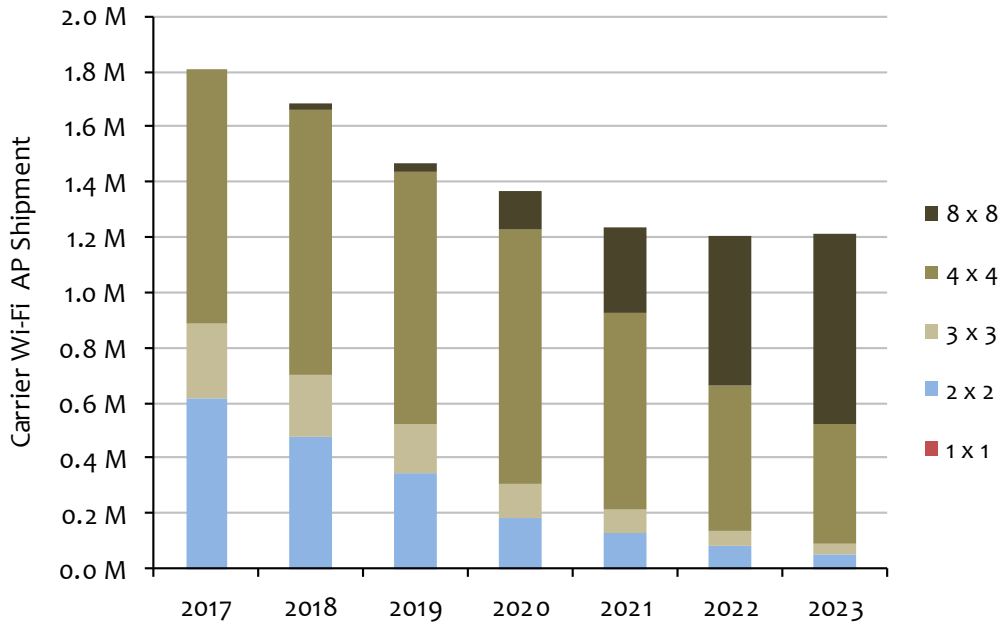


Source: Mobile Experts

Chart 17: Carrier Wi-Fi 60 GHz AP Shipment Forecast, Backhaul/FWA, 2017-2023

Carrier Wi-Fi MIMO Trend

A majority of Carrier Wi-Fi access equipment supports MIMO since it was introduced with 802.11n. Using MIMO results in greater data rates, improved range, and overall improvement in Wi-Fi network performance. The introduction of multi-user MIMO (MU-MIMO) in 802.11ac wave 2 has been well received in Carrier market segment where network congestion is a major problem. In essence, MU-MIMO alleviates network congestion by allowing multiple client devices to access the radio channel (assuming those client devices also support MU-MIMO). With MU-MIMO, even 1x1 legacy Wi-Fi clients can be serviced through an access point. With increasing adoption of 802.11ac and eventually 802.11ax, high-order MIMO configuration (i.e., 4x4 and 8x8) is expected to dominate share of Carrier Wi-Fi access equipment going forward.

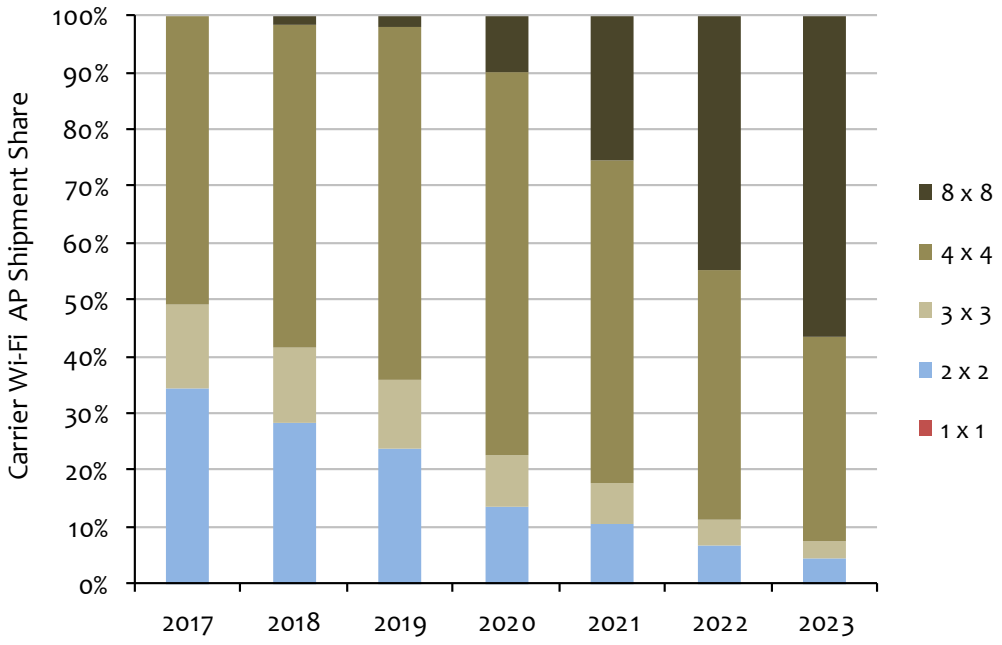


Note: Only captures Wi-Fi integrated broadband CPEs; Excludes video set-top CPEs

Source: Mobile Experts

Chart 18: Carrier Wi-Fi MIMO Configuration Trend, 2017-2023

While some high-end 802.11ac products (e.g., Quantenna's "10G wave 3" chipset) support 8x8 MIMO, a bulk of Carrier Wi-Fi products supporting 8x8 is expected to roll out en masse in 2020 and beyond as 802.11ax transition takes a full effect.



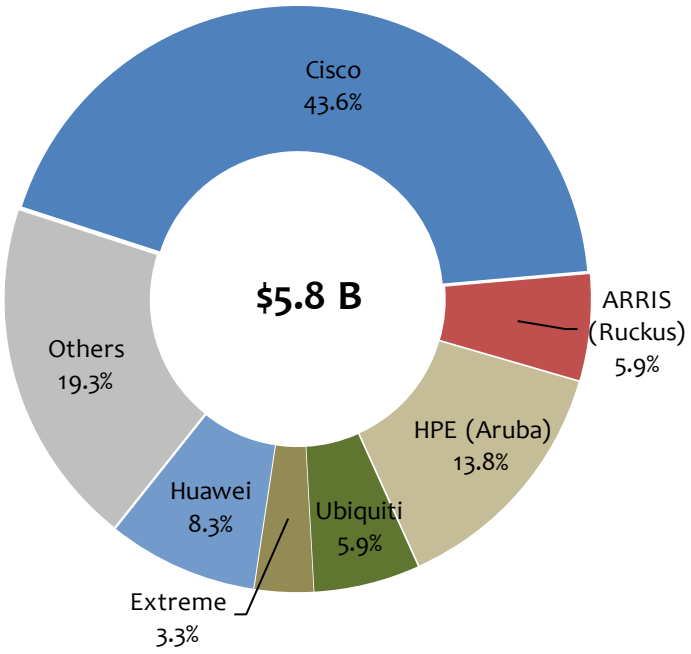
Source: Mobile Experts

Chart 19: Carrier Wi-Fi MIMO Configuration Share, 2017-2023

Market Share of Wi-Fi AP Vendors

The Carrier Wi-Fi infrastructure equipment market can be segmented into standalone APs and Wi-Fi integrated CPEs. While there is a significant unit volume and absolute dollar count to the CPE category vs. AP, the Carrier Wi-Fi AP equipment carry relatively higher per unit pricing. Hence, we have focused our market share analysis specifically on the AP category in this year's report. Please note that the major vendors in the CPE category are the leading telecom infrastructure vendors including Huawei, ZTE, ARRIS, and others.

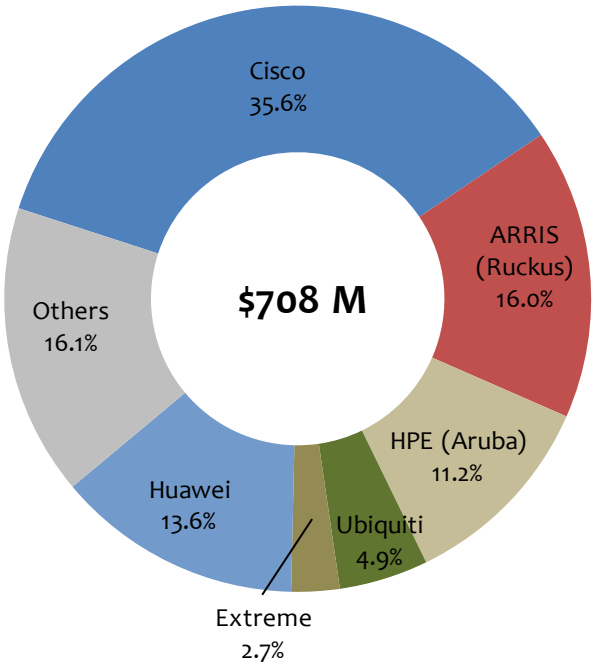
It should be noted that the overall Wi-Fi AP vendor landscape is dominated by Enterprise WLAN players such as Cisco, HPE (Aruba), and others, and the carrier segment is a smaller piece within the overall WLAN market. With its strong presence in the enterprise networking market, Cisco dominates the overall WLAN market by a wide margin. It holds over 40% of the total WLAN equipment market share in revenue terms. Its closest rival, HPE (Aruba), holds about one-third in wireless revenue. We estimate that the overall enterprise wireless market is growing at high single digits and expect the traditional Wi-Fi AP vendors to focus on the enterprise space for the foreseeable future.



Source: Mobile Experts

Chart 20: Overall WLAN Equipment Revenue Share, 2017

The Carrier Wi-Fi market is characterized by Wi-Fi AP equipment sold directly to service providers. While it is arguably difficult to track which Wi-Fi AP products sold to enterprise or service provider channels, we estimate the certain vendors are more specifically focusing on the service provider segment over numerous enterprise vertical channels (e.g., hospitality, education, healthcare, etc.). Based on our checks and discussions with vendors, we estimate that the overall Carrier Wi-Fi market is just over 10% of the overall WLAN market today. Even in the Carrier Wi-Fi segment, Cisco leads the market with about 40% of the overall share, followed by Ruckus (now part of ARRIS), then closely followed by Huawei and HPE (Aruba). Excluding the Wi-Fi integrated CPE market segment, we expect the Carrier standalone AP segment will continue to decline as "converged" mobile/telco operators look to LTE-unlicensed technology to leverage unlicensed spectrum. As the Carrier Wi-Fi standalone AP market declines, we expect smaller Wi-Fi vendors to focus their efforts towards the enterprise market. For example, Ubiquiti has been focusing their product and sales strategy towards the enterprise market and now derives more business from the enterprise market than service provider segment.



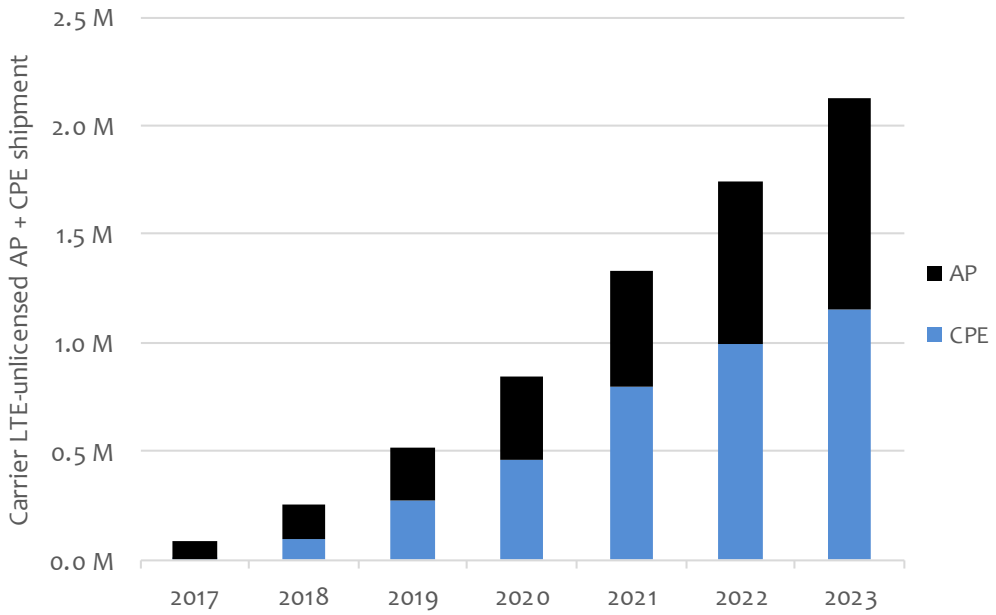
Source: Mobile Experts

Chart 21: Carrier Wi-Fi Infrastructure Revenue Share, 2017

It should be noted that ARRIS and Huawei remain two major vendors who have sizable businesses in both the Carrier Wi-Fi standalone AP and CPE businesses. Traditional enterprise WLAN vendors seem content to focus on the enterprise market which remain higher-margin businesses compared to the service provider CPE business which carry significant volume, but at a razor-thin profit margin.

6 "LTE-UNLICENSED" (LAA, CBRS, MULTEFIRE) OUTLOOK

The LTE use in the unlicensed and shared spectrum through LAA, CBRS, and MulteFire ("LTE-unlicensed") is expected to incrementally add to the overall carrier wireless infrastructure market. Our overall expectation for this "LTE-unlicensed" segment of the overall carrier unlicensed wireless infrastructure market has diminished slightly from last year as a result of CBRS regulatory delay and niche market opportunity for MulteFire. Our reduced expectation in CBRS and MulteFire segments is offset by almost doubling of LAA small cell shipments. It appears that operators want to have the option of using LAA to leverage the unlicensed spectrum for high-speed mobile service, if they need it. Our checks with small cell vendors indicate higher shipment counts for LAA multiband units. Vendors are building LAA into small cells, even if operators do not have immediate plans to light LAA up.



Source: Mobile Experts

Chart 22: Carrier "LTE-unlicensed" AP and CPE Shipment, 2017-2023

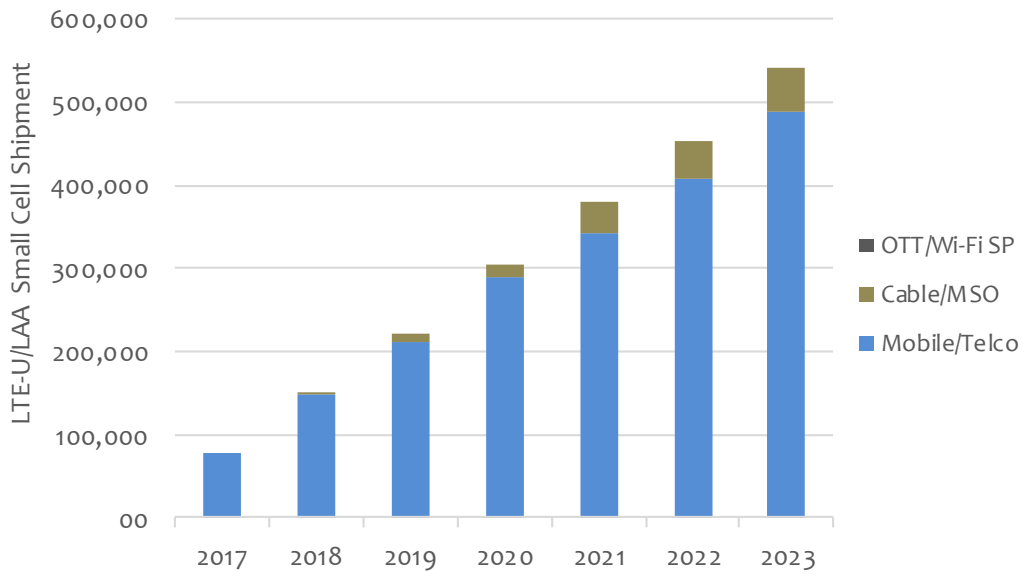
In terms of AP vs. CPE breakdown, the LTE-unlicensed access equipment shipment is somewhat evenly split between standalone access point (AP) and customer premise equipment (CPE) units. The majority of the CPE units pertain to CBRS radios embedded in broadband gateway units deployed by the cable operators and fixed wireless CPE units deployed by telco/cable/OTT providers. For LAA, we expect the mobile operators to primarily use LAA small cells to service mobile devices. There is a lot of uncertainty around how aggressive cable operators will leverage its "inside-out" strategy (i.e., CBRS-integrated broadband gateways into its huge base of fixed broadband subscribers). Hence, the CPE projection – about half of which are based on the cable operators' "inside out" deployment – can widely vary.

LAA Shipment Forecast

Mobile Experts expects LAA to be the dominant means by which mobile operators will leverage unlicensed and shared spectrum bands below 6 GHz. The licensed-assisted manner in LAA allows the mobile operators to effectively leverage the unlicensed "public" spectrum for its "private" use by managing service quality through control signaling on licensed anchor band, which is, by definition, exclusive to a mobile operator. Mobile Experts expects the mobile operators to opportunistically leverage the unlicensed 5 GHz band in the near term, and the 3.5 GHz CBRS band, under PAL license, to increase capacity. In concert, we expect the operators to tout "Gigabit LTE" services as they expand small cell rollouts with LAA and CBRS multiband capabilities and seed the market with Category 16 (1Gbps downlink) smartphones. This trend has already started and is expanding as operators complete trials and announce 4.5G LTE-Advanced Pro network rollouts. According to Global Mobile Supplier Association (GSA), there are already 39 LTE-Advanced Pro networks live and more are coming.[8]

In general, Mobile Experts expects mobile operators with limited licensed spectrum holdings to leverage LAA to expand capacity and user throughput speeds. For example, T-Mobile and Verizon have been very public about their intentions to deploy LAA, and its predecessor, LTE-U, networks. T-Mobile has upgraded its LTE-U network to LAA networks in late 2017, and we expect Verizon is follow suit. Mobile Experts believes that the 5 GHz band may not be heavily loaded in urban environments for outdoor applications as most of Wi-Fi deployments are for indoor applications with low-power radios. For this reason, we expect mobile operators to take advantage of this situation by deploying LAA small cells initially for outdoor applications at key strategic locations such as public venues like stadiums and transportation hubs so that they can claim "Gigabit LTE" services as they rollout Category 16 user devices.

[8] GSA, Gigabit LTE snapshot, May 2018.



Note: includes predecessor LTE-U units

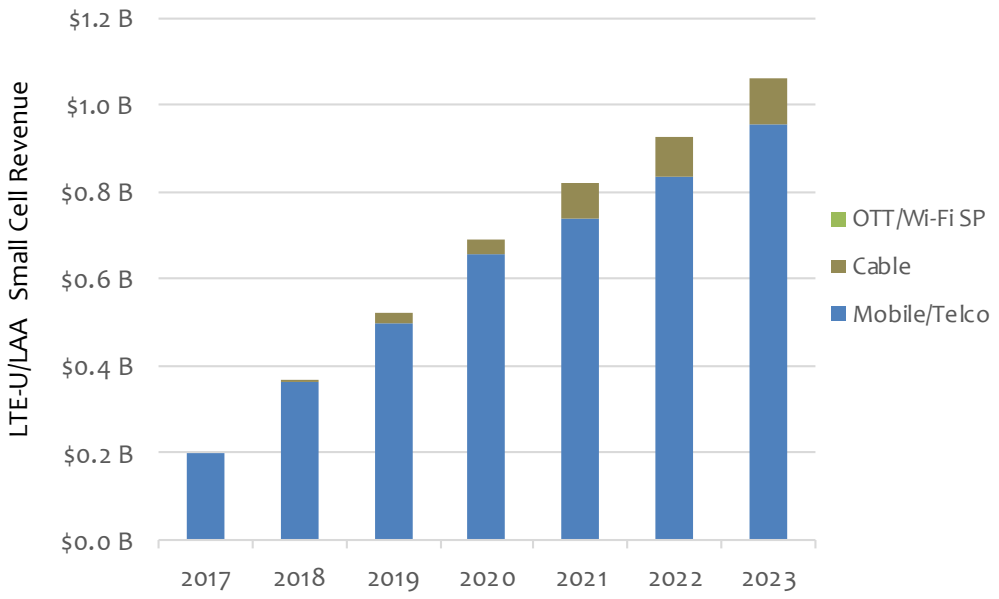
Source: Mobile Experts

Chart 23: LAA Shipment Forecast by Operator Segment, 2017-2023

There is a possibility that cable operators may also deploy LAA with licensed or CBRS PAL spectrum to augment mobile network capacity on its own facilities-based network. There is a lot of uncertainty around this prospect, but we have denoted this possibility in our forecast starting 2019 in anticipation of the CBRS PAL auction taking place then.

LAA Revenue Forecast

Outside of Carrier Wi-Fi, LAA represents the next biggest carrier unlicensed wireless infrastructure market opportunity and growing the fastest – from just under $200M in 2017 to about $1.1 B by 2023. Because of the nature of reliance upon licensed spectrum for the "anchor" carrier, LAA is mainly reserved for the mobile operators. However, we expect the U.S. cable operators to leverage the 3.5 GHz shared spectrum as the anchor carrier and leverage LAA for the additional spectrum access to deepen its mobile network capacity. In the end, LAA will be most appealing to the mobile operators with limited spectrum holdings, and the mobile operators will be the primary beneficiaries of this technology.

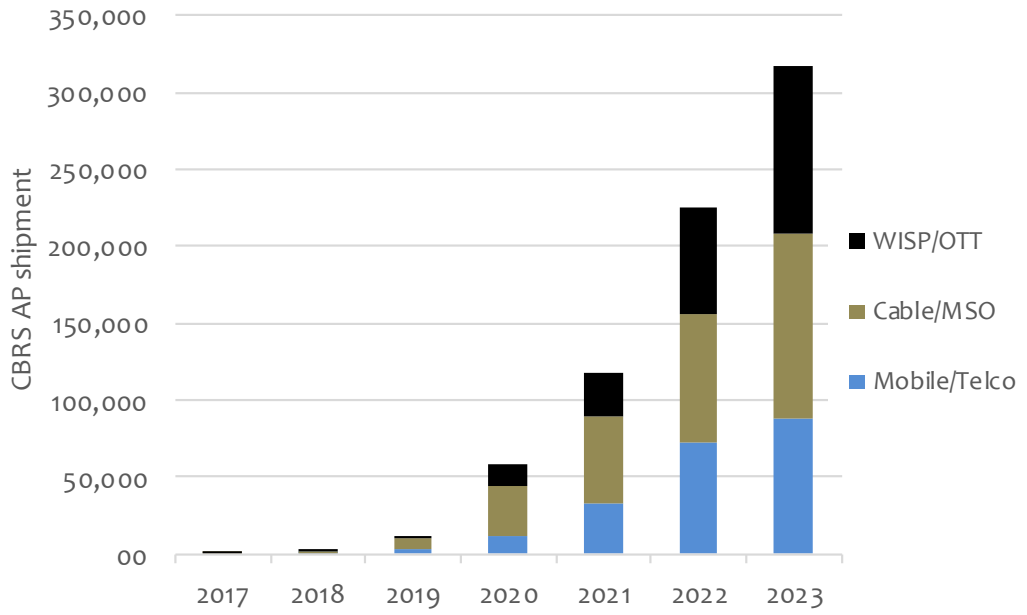


Source: Mobile Experts

Chart 24: LAA Equipment Revenue by Operator Segment, 2017-2023

CBRS Shipment Forecast

The CBRS ecosystem has attracted many diverse members ranging from chipsets, system vendors, and all major operators in the United States. While the key stakeholders eagerly await the final FCC ruling on key licensing terms like geographic size, licensing term duration, etc., about a year-long delay has brought the ecosystem to mature. SAS and ESC providers have been through multiple integration testing and trials with mobile and cable operators, and the whole ecosystem is eagerly anticipating FCC final ruling sometime in 2019. While the GAA operation can take place once the SAS and ESC systems are certified, which is expected at the end of 2018, meaningful system deployments by the mobile operators and cable operators aren't likely until 2020. As a result, our forecast of the CBRS unit shipments have been brought down since our last update.



Note: Excludes AP units related to fixed wireless access application

Source: Mobile Experts

Chart 25: Carrier CBRS AP Shipment Forecast, 2017-2023

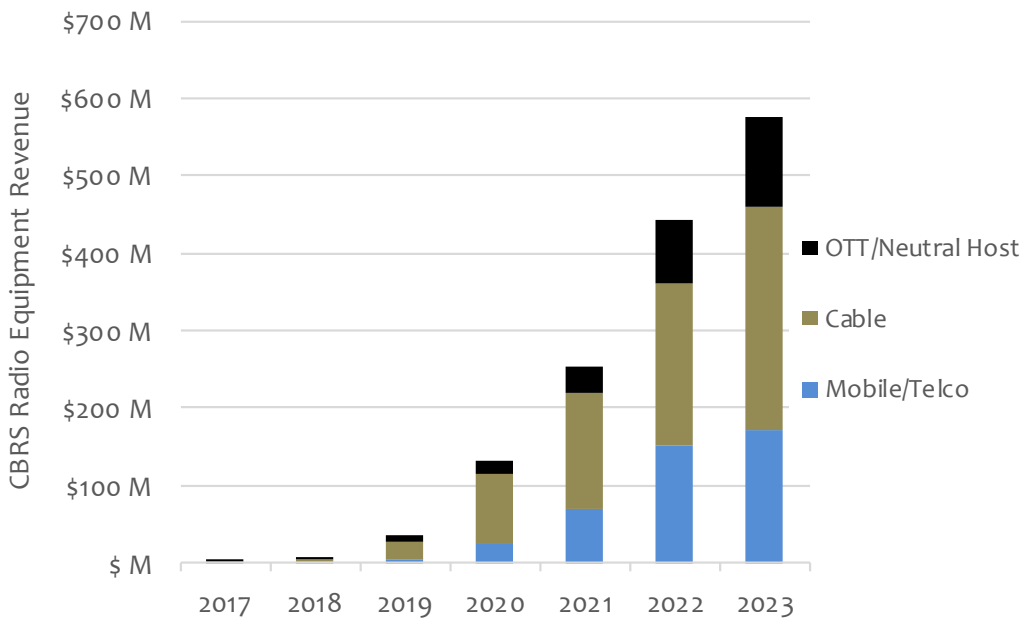
While the initial CBRS infrastructure AP and CPE shipments in 2018 and 2019 will largely operate under GAA operation for fixed wireless and some initial in-building/neutral host applications, Mobile Experts forecast the meaningful volume of infrastructure equipment to pick up in 2020, once PAL licensing terms have been finalized and cleared. We expect the mobile and cable operators to be main stakeholders who will deploy CBRS infrastructure. The mobile operators will likely use the 3.5 GHz band as an additional carrier aggregation band for LAA. Meanwhile, the cable operators will likely view the band as a primary anchor band (once PAL licenses are obtained) and leverage its extensive Wi-Fi infrastructure for mobile offload. There is a possibility that the operators may integrate CBRS in place of Wi-Fi on CPE devices to extend mobile coverage (as a part of "inside-out" strategy) or for fixed wireless application. We have accounted for this possibility in our forecast, but we have placed a conservative estimate on this possibility. As shown above, Mobile Experts is forecasting the cable operators to be main stakeholders in deployment of CBRS AP gears as well as CPEs. With the U.S. cable operators' latest entry into the wireless business, we believe that they are motivated to deploy the new shared spectrum aggressively to expand their own facilities-based network capacity.

The overall CBRS access equipment market is poised for tremendous growth, despite the delay in final regulatory ruling. Starting from a small base, our three-digit percentage growth in shipments is plausible considering that multiple operator groups and some large enterprises are active in the ecosystem. While there is a lot of uncertainty around the size of the market (as the final FCC ruling has not taken place), we believe there is enough

momentum and investments in the ecosystem to see market adoption in the next year. The size of the market and the pace of deployments will certainly depend on the final ruling.

CBRS Revenue Forecast

With diverse applications and presumably a lower cost of spectrum access, CBRS offers something for everybody. Mobile and cable operators can leverage relatively cheaper CBRS spectrum for mobile services while OTT operators can leverage the 150 MHz of "clean" spectrum for fixed wireless service. Meanwhile, some large enterprises may view the spectrum use for private LTE or in-building wireless services. As a new entrant to wireless, Mobile Experts expects the cable operators to be very active in utilization of CBRS for multiple facets of their mobile and/or fixed broadband services.



Note: Excludes revenue contribution related to fixed wireless access application

Source: Mobile Experts

Chart 26: Carrier CBRS Radio Equipment Revenue Forecast, 2017-2023

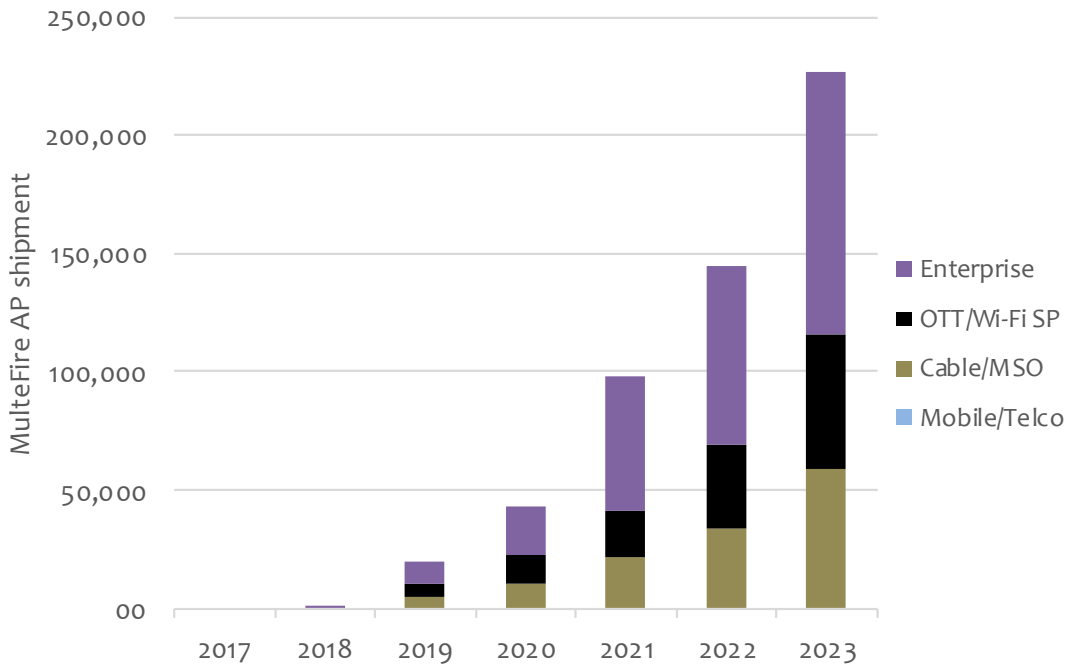
LTE-Wi-Fi Aggregation (LWA) Outlook

While LWA has been trialed and launched on limited basis, the idea of leveraging existing Wi-Fi infrastructure along with LTE to aggregate link speed and capacity has received a lukewarm reception by the mobile operators. We are not aware of any additional trials or commercial deployments of LWA since the limited trials at Chunghwa Telecom in Taiwan and M1 in Singapore. The technology appeal of LWA is limited among the mobile operators who, we believe, view LAA and eLAA more favorably as more elegant means to leverage

unlicensed spectrum for mobile data use. As a result, we are no longer tracking LWA radio shipments in this report. While there is a remote chance that other operators such as cable operators who have extensive Wi-Fi infrastructure to adopt LWA, we currently view this as a small probability as even they appear more inclined to adopt the next-generation 802.11ax and LTE in CBRS as possible means for their mobile service offering.

MulteFire Shipment Forecast

MulteFire attempts to broaden the appeal of LTE use in the unlicensed bands by allowing "standalone" LTE to run in the unlicensed bands without a licensed anchor. In effect, MulteFire allows anyone without licensed spectrum holdings to run LTE. There is a perceived value of being able to run LTE to take advantage of higher service quality afforded with coordinated and deterministic scheduling in LTE vs. "collision avoidance" scheduling in Wi-Fi. In fact, there is consumer value, since consumers are willing to pay more for "LTE" than they will pay for "Wi-Fi". It is still too early to assess the merits of 802.11ax vs. MulteFire in the 5GHz unlicensed band or the 3.5 GHz shared band, but Mobile Experts expects some cable operators, OTT/neutral host providers, and a few large enterprises to adopt MulteFire on a limited trial basis to assess its merit with respect to 802.11ax. Business cases for MulteFire still need to be proven out, such as neutral host in-building wireless.



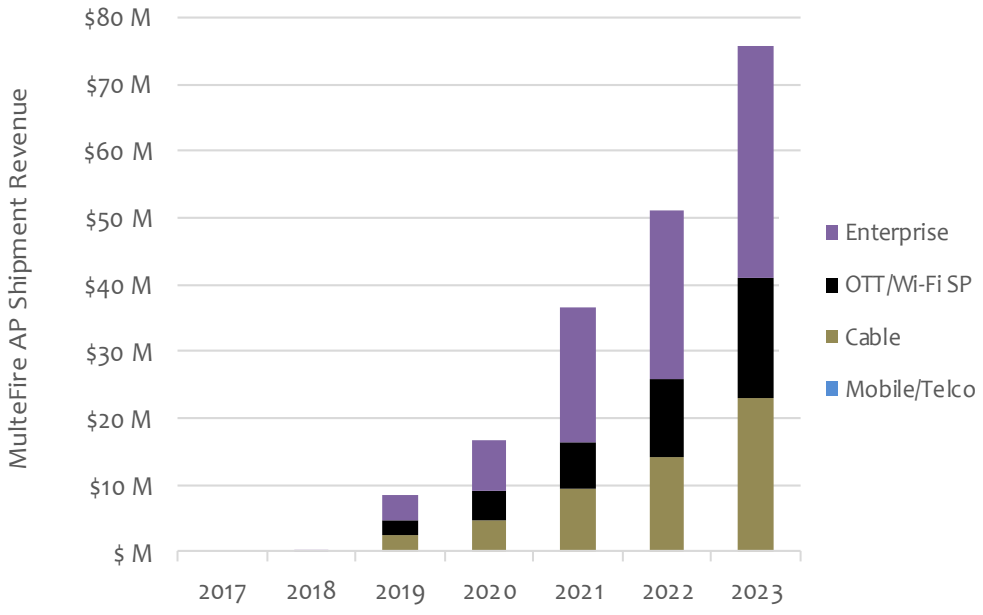
Source: Mobile Experts

Chart 27: MulteFire AP Shipment Forecast by Operator Segment, 2017-2023

MulteFire is expected to be trialed by non-mobile operators like the cable operators, OTT/neutral host providers, and enterprises. With the MulteFire spec 1.0 for mobile broadband recently released, Mobile Experts predicts the carrier demand for MulteFire will largely be confined to non-mobile operators and scale of rollout will likely be limited. For the MulteFire segment to scale, the economics of MulteFire and specific use cases targeted must be meaningfully differentiated against other technology and ecosystem alternatives. Thus far, such differentiations are few, and Mobile Experts forecasts a modest uptake in the near term. We believe some large enterprises may look to MulteFire for "private LTE" deployments whereby enterprises deploy standalone LTE network on unlicensed bands for specific enterprise application.

MulteFire Revenue Forecast

Similar to CBRS, MulteFire represents an opportunity for different operators to leverage LTE in the unlicensed spectrum bands. With many key advancements forthcoming with the 802.11ax transition, niche application of MulteFire is not yet clear. For general wireless broadband connectivity, we believe the operators and enterprises alike will choose other technology options before resorting to this technology. Hence, the market opportunity is small at this early stage of adoption. Again, enterprise group is expected to be most active stakeholders in this category compared to traditional service provider groups.



Source: Mobile Experts

Chart 28: MulteFire Equipment Revenue by Operator Segment, 2017-2023

Market Share of "LTE-unlicensed" Vendors

As the market for "LTE-unlicensed" segment of the overall carrier unlicensed wireless infrastructure market is still very formative in its lifecycle, a market share chart for this particular segment of the overall market is not yet provided. As the market matures, we look forward to charting the market share of the LTE-unlicensed sector, including LAA, MulteFire, and CBRS. For now, it is reasonable to expect that the major infrastructure vendors like Ericsson, Nokia, and perhaps ARRIS to make a play for the "LTE" side of the carrier unlicensed wireless infrastructure market.

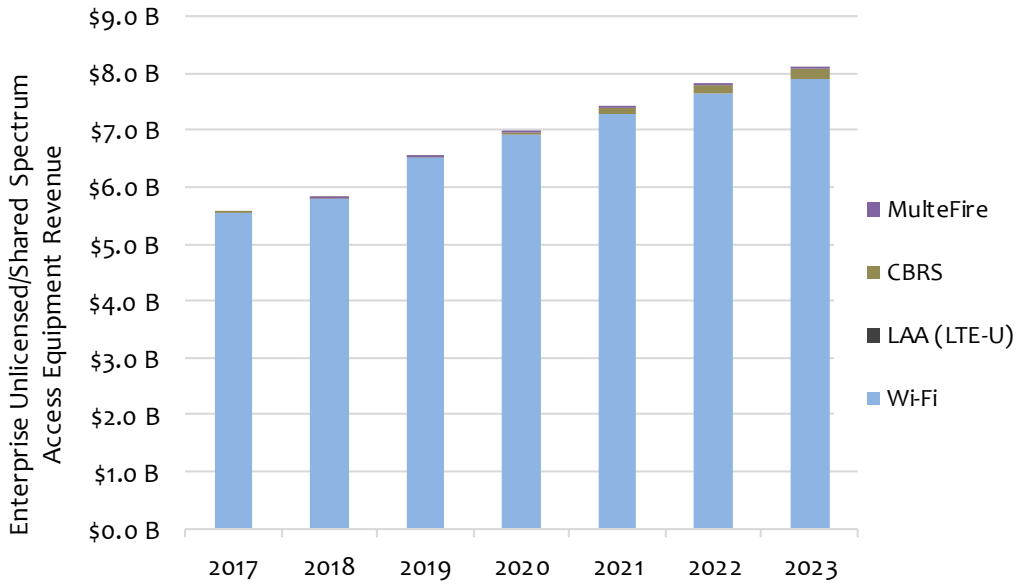
Impact of LTE-Unlicensed on Enterprise WLAN Market

While this report specifically focuses on the Carrier market, in the course of our analysis, we try to gauge how might LTE for unlicensed and shared spectrum ("LTE-unlicensed") technologies such as LAA, CBRS, and MulteFire might impact the Enterprise WLAN market. Will the LTE-unlicensed technologies swiftly take share away from Wi-Fi infrastructure market in the enterprise space? Before LAA and MulteFire, both the carriers and enterprises relied solely on Wi-Fi to take advantage of unlicensed spectrum. With LTE-unlicensed technology coming to market, there appears to be a direct competition between Wi-Fi and LTE at a surface level.

Mobile Experts believes that the "us vs. them" dynamic between Wi-Fi and LTE communities is overblown. The two technologies fundamentally serve different end markets that is historically rooted in their origins. We expect certain niche segments of the enterprise market to adopt "standalone" LTE-Unlicensed technology such as MulteFire in the unlicensed and shared spectrum bands. At the same time, a predominant base of the enterprise market will continue to adopt the traditional Wi-Fi technology roadmap, upgrading from 802.11n and 802.11ac base to 802.11ax in the near future. Moreover, the traditional enterprise Wi-Fi market will likely adopt 60 GHz spectrum use through 802.11ad and 802.11ay in some cases such as wire replacement and "tri-band" (2.4 GHz, 5 GHz, and 60 GHz) router deployment use cases. Considering the huge Enterprise Wi-Fi infrastructure market, the LTE penetration of the traditional Enterprise Wi-Fi market, namely through MulteFire on the 5 GHz and 3.5 GHz CBRS bands, is expected to be *de minimis*.

In a closer look, Mobile Experts believes that enterprise adoption of LTE-unlicensed technologies such as LAA, MulteFire, and CBRS is very limited. With the next Wi-Fi technology transition to 802.11ax about 1-2 years way, we expect the enterprise market to eagerly adopt 802.11ax. The OFDMA and 8x8 MU-MIMO features in 802.11ax will provide efficiency gains in both the 2.4 GHz and 5 GHz bands. Some niche enterprise applications in the 3.5 GHz CBRS band will provide some added market opportunity for LTE adoption but most of that will likely reside in the "fresh" 3.5 GHz band. The majority of $6-$8B enterprise WLAN market opportunity in the 2.4 GHz and 5 GHz bands will continue to rely on Wi-Fi (transitioning from 802.11ac to 802.11ax). The LTE-unlicensed portion of the enterprise

wireless infrastructure market is expected to constitute only 3% of the total enterprise wireless market in 2023.



Source: Mobile Experts

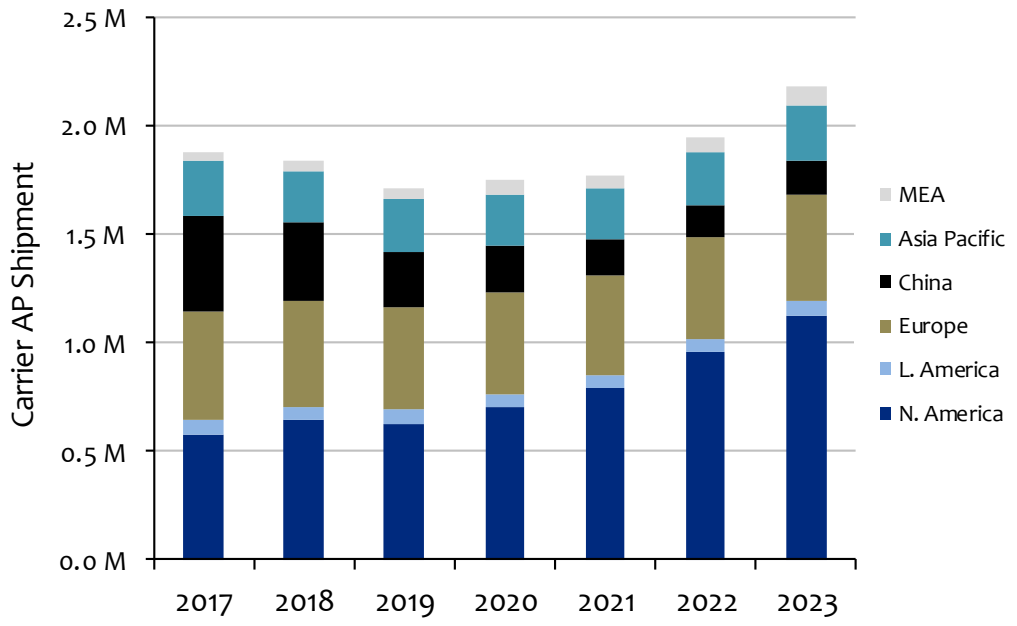
Chart 29: Enterprise Unlicensed Radio Equipment Revenue by Technology, 2017-2023

In summary, Mobile Experts believes that LTE use in the unlicensed and shared spectrum bands through CBRS and MulteFire will not meaningfully impact the enterprise WLAN market. Instead, CBRS and MulteFire will open new market opportunities in the enterprise market in new use cases and applications such as "private LTE" and IoT. The LTE-unlicensed use will not be a "zero-sum game" to the enterprise WLAN market.

7 REGIONAL OUTLOOK

The carrier-grade access point (AP) shipment including LTE-unlicensed and Wi-Fi access point units is forecasted to grow at over 3% CAGR (2017-2023) to reach over 2M units in 2023. This is a slight increase from last year's forecast primarily due to increased forecast of LAA equipment offset by the slight delay in CBRS rollout and lack of LWA adoption in the marketplace. Overall, the carrier unlicensed infrastructure market is transitioning through the "Wi-Fi to LTE-unlicensed" lull as the Carrier standalone Wi-Fi market declines while the LAA, CBRS and MulteFire ("LTE-unlicensed") ecosystems ramp up. Once the LTE-unlicensed ecosystems fully ramp up, the market is expected to pick up momentum.

Regionally, North America is expected to see the strongest growth as competitive market dynamics is forcing multiple operator stakeholders to seek cost-effective mobile solution using unlicensed and shared spectrum bands. In addition, the CBRS ecosystem is expected to bring additional players including the cable operators and OTT/neutral host providers to make infrastructure investment in this band. Other regions where licensed spectrum is limited such as parts of Asia-Pacific and MEA are also expected to leverage LAA to bolster network capacity.



Source: Mobile Experts

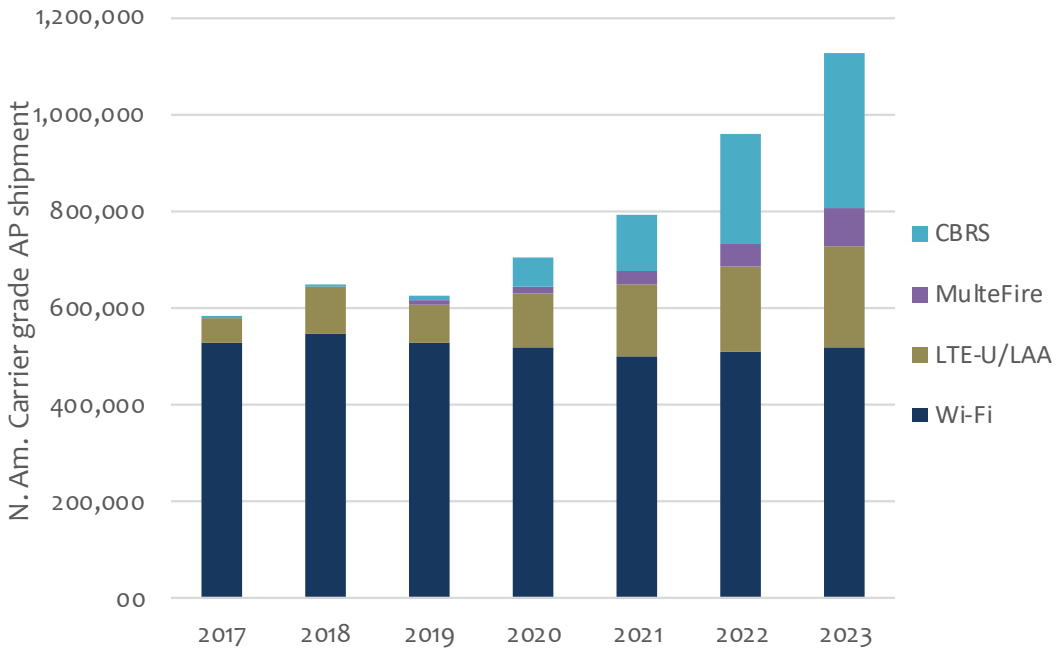
Chart 30: Carrier Unlicensed AP Shipment by Region, 2017-2023

North America

The North American region represents the biggest market for the "carrier unlicensed radio infrastructure" market with combined shipment of 600,000 standalone AP units across

Carrier Wi-Fi, LAA, CBRS, and MulteFire in 2023. Mobile Experts forecasts a mid-single-digit decline in traditional Carrier Wi-Fi segment from 2017 to 2023 as mobile operators, shift investment towards LTE-based technologies, primarily LAA and CBRS. Mobile operators will lead the transition but we expect cable operators to follow to a lesser degree.

The overall carrier unlicensed AP market is expected to grow at over 20% through 2023. The combined CBRS and LAA AP equipment is forecasted to represent the largest share of the overall unlicensed/shared carrier access equipment market with about 35% each in 2023. A significant share of CBRS is largely based on the assumption that the current CBRS rules will be maintained and that cable operators, OTT/neutral host providers, and some large enterprises, will make capital investment in CBRS radios alongside the mobile operators. It is still not clear whether the final CBRS rules will favor larger mobile operators vs. smaller OTT providers. We have largely kept our CBRS growth forecast assumptions with a key caveat that our growth forecast now delayed by about a year later than our previous forecast. It should be noted that Mobile Experts believes that a bulk of CBRS units deployed by mobile operators will be employed in LAA carrier aggregation, while cable operators will deploy in a standalone TD-LTE mode.



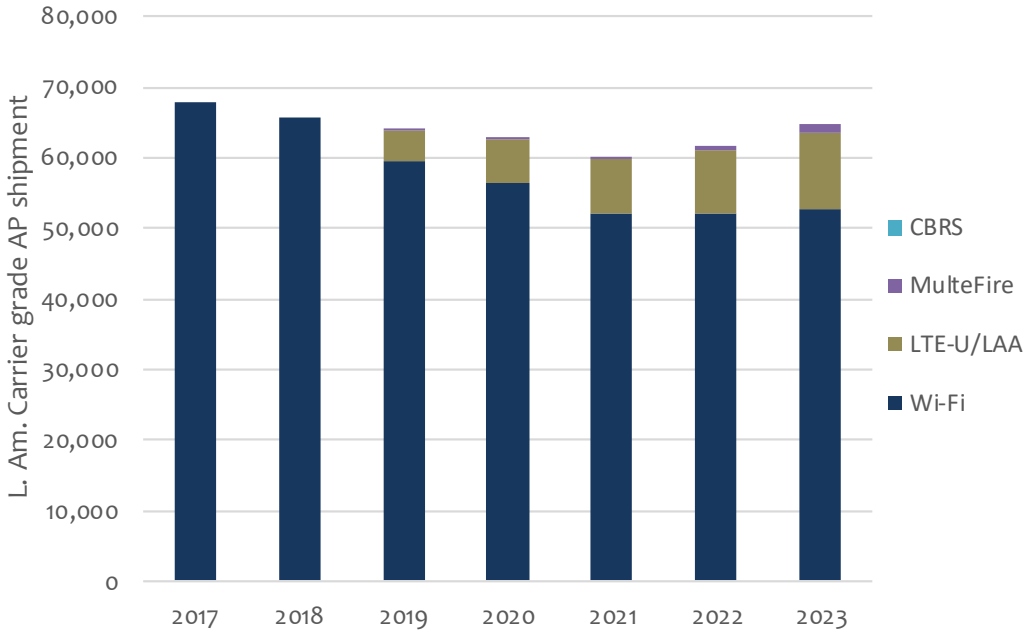
Source: Mobile Experts

Chart 31: Carrier Unlicensed AP Shipment, North America, 2017-2023

Latin America

The scale of carrier AP shipments in Latin America pales in comparison to the North American market. However, the mobile operators in the region are expected to adopt LAA

as the learnings from field trials in the leading markets in North America and Europe become well understood. In fact, we are aware of Claro in Brazil already demonstrating "Gigabit LTE" via trial and lab testing. As the LAA infrastructure and client device ecosystems mature and gain scale, we expect the leading mobile operators in the region to selectively deploy LAA to augment capacity. The initial LAA deployments is likely to be limited in scope. In the near term, Carrier Wi-Fi in public hotspot locations will be used for mobile offload. The overall market is expected to be flat or slightly down as the traditional Carrier Wi-Fi segment declines while LAA deployments slowly ramp up.



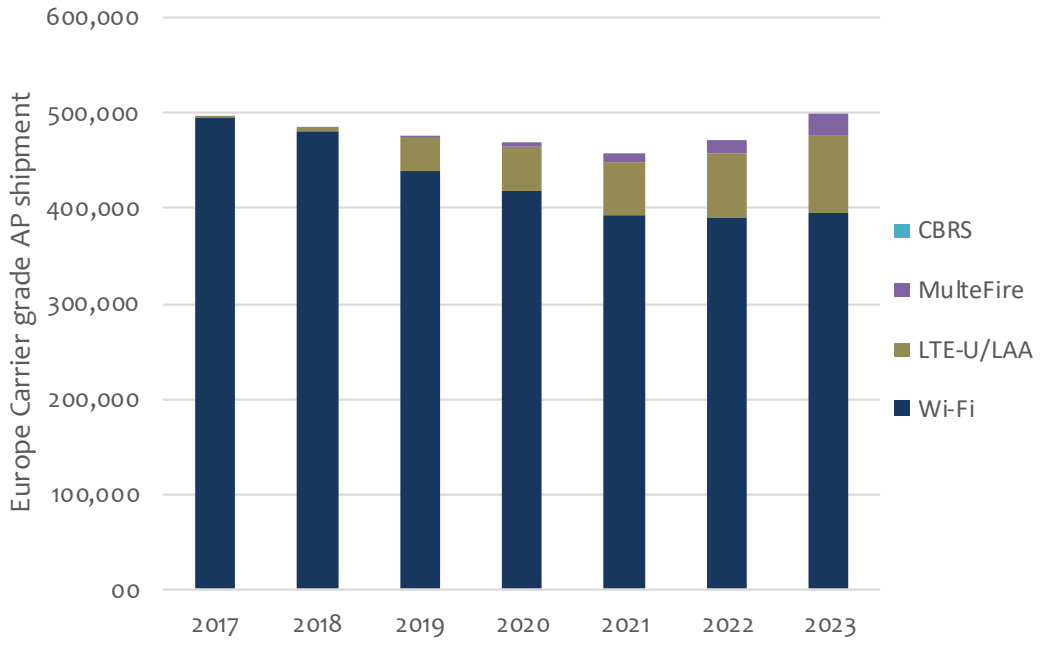
Source: Mobile Experts

Chart 32: Carrier Unlicensed AP Shipment, Latin America, 2017-2023

Europe

With a diverse mix of fixed and mobile operators, Europe represents the second biggest market for carrier unlicensed infrastructure market. Mobile Experts forecasts higher growth prospects for LAA in the region--fueled by "quad play" competitive dynamics. While some major operators have conducted LTE-U and LAA trials in the past year, announcement of scale deployments has been somewhat muted. The major operators including Deutsche Telekom, Telefonica, and TIM and a couple of major Russian operators have testing and trials at varying stages. We expect these trials to lead to commercial-scale deployments in the near future. With mobile and fixed operators largely settling into a more stable competitive environment after a flurry of mergers and acquisitions in the past year, Mobile Experts expects major operators to opportunistically deploy LAA small cells on path towards LTE-Advanced Pro network rollouts before 5G NR commercial rollouts happen sometime in

2021-2022 timeline. Mobile Experts expects opportunistic MulteFire adoption as some enterprises look to test out "private LTE" applications for factory automation in preparation for 5G low-latency applications.



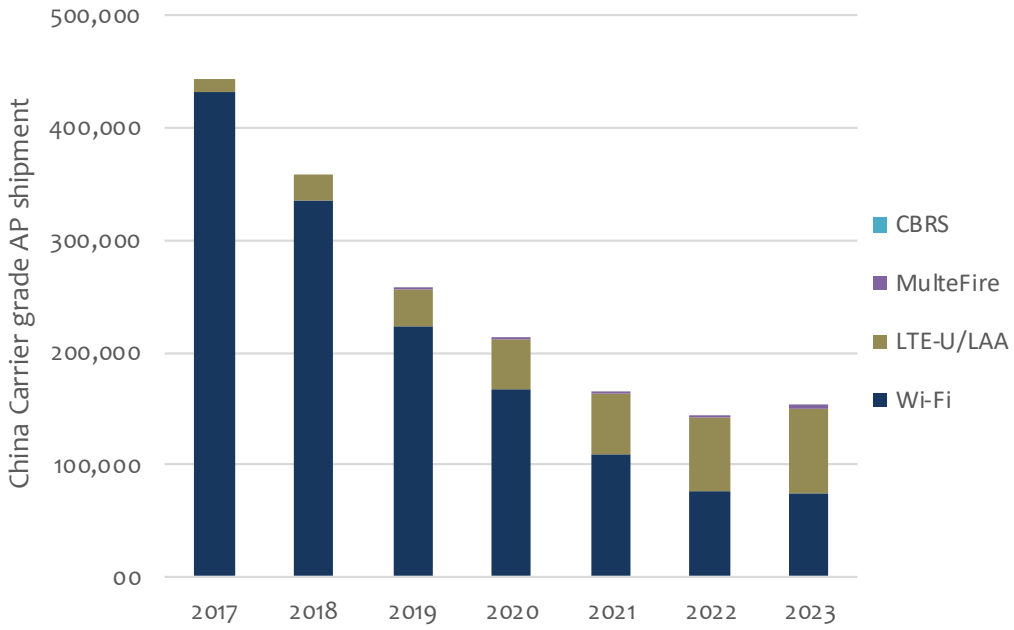
Source: Mobile Experts

Chart 33: Carrier Unlicensed AP Shipment, Europe, 2017-2023

China

Mobile Experts expects a continual decline in the traditional carrier Wi-Fi standalone AP shipments in China. While there will be sporadic public hotpot deployments, we believe Chinese operators clearly see spectrum roadmap in the C-band for the upcoming 5G rollout. The use of unlicensed spectrum will be largely kept to Carrier Wi-Fi and LAA use will be opportunistic and far fewer for a region with tremendous user base and traffic growth. While we had expected China Mobile with a significant installed base of Wi-Fi access points to leverage LWA to augment network capacity, we now believe Chinese operators will largely look to Wi-Fi upgrades and selective LAA deployment. The Chinese operators are gearing up for massive 5G network deployment next year in the 3-4 GHz band. While we hold on to the view that the Chinese operators with relatively limited licensed spectrum holdings (i.e., China Unicom and Telecom) may be inclined to adopt LAA, we have not seen hard evidence that they are actively pursuing this strategy.

In short, China is focused on 5G, and strategies to use lower cost upgrades in unlicensed spectrum are on the back burner. There is a lot of uncertainty around LAA adoption in China if that happens at all.

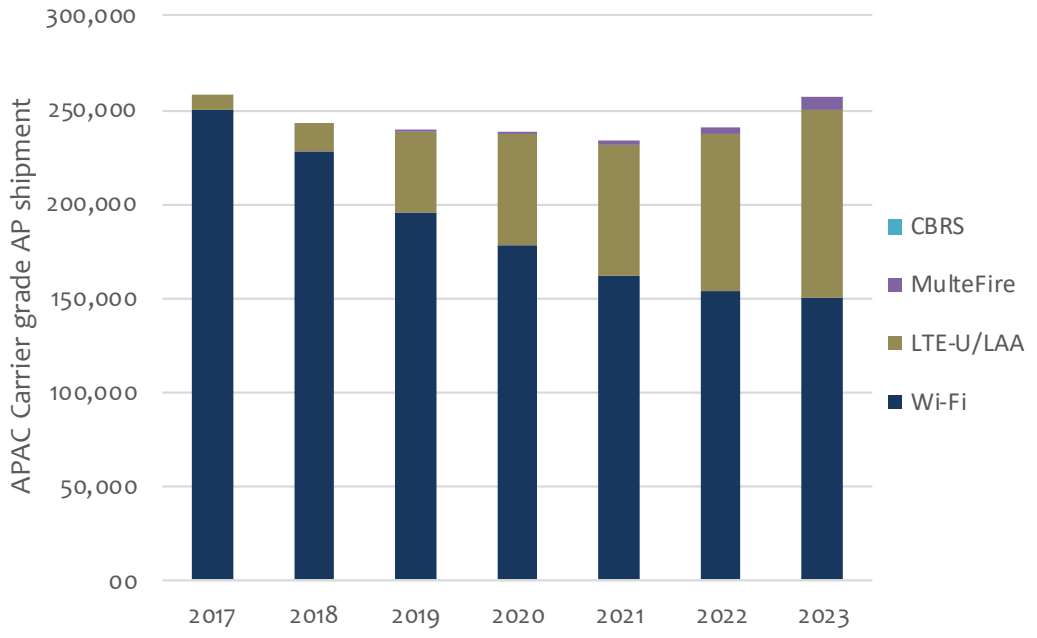


Source: Mobile Experts

Chart 34: Carrier Unlicensed AP Shipment, China, 2017-2023

Asia Pacific (excluding China)

Some of the leading operators in Korea and Japan have trialed various LTE-unlicensed technologies including LWA/LWIP, LAA, etc. The limited LWA/LWIP deployment has not gained much traction, and the fate of its deployment is suspect at this point. Major mobile operators in Korea, Japan, Indonesia, and others in Southeast Asia have conducted active trials and testing. Mobile Experts expects these trials will turn into scale rollouts in 2019, and that Carrier Wi-Fi standalone AP deployments will wane. Mobile Experts forecasts the overall carrier unlicensed radio infrastructure AP shipments to remain fairly flat during our forecast period. We expect the mobile operators with limited licensed spectrum holdings will look to LAA instead of Carrier Wi-Fi offload to handle traffic growth. The LAA feature initially found in 2017-2018 premium smartphones will gradually transition to 2019-2020 "mainstream" smartphone line-up, which is a "sweet spot" for Southeast markets.

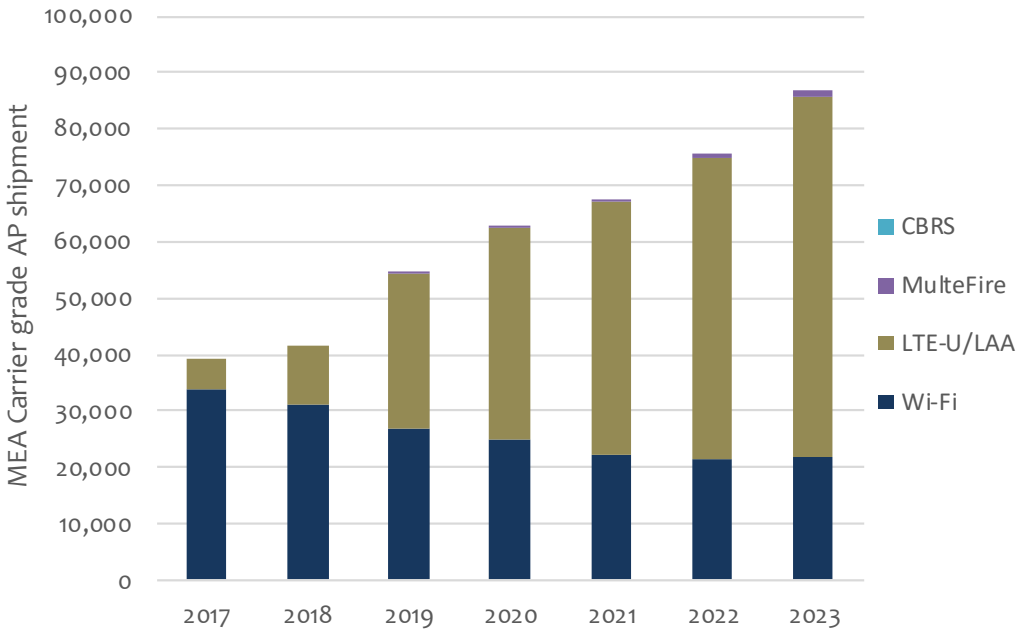


Source: Mobile Experts

Chart 35: Carrier Unlicensed AP Shipment, Asia-Pacific, 2017-2023

Middle East/Africa

The Middle East/Africa (MEA) region is very diverse. The developed markets like Dubai, Turkey, and South Africa continue to advance their network capabilities and deploy the latest LTE features. In Turkey, for example, all three major mobile operators have already deployed LTE-Advanced Pro network features in select markets. For these high-end segment of the region, Mobile Experts expects mobile operators to eagerly deploy LAA small cells along with high-end smartphone introduction to tout "Gigabit LTE" services over the next couple of years. Vodafone operating companies in Turkey and South Africa have already announced LAA deployments with several vendors including Huawei, Ericsson, and Spidercloud. For operators with limited licensed spectrum holdings in South Africa for example, LAA small cells offer a scalable solution to increase network capacity. Starting from a small base, Mobile Experts expects a robust growth overall with LAA making up almost 90% share of the total unlicensed carrier access equipment shipped in the region in 2023. It's strong growth, but the relatively low number of small cells means that LAA market size in MEA will be limited by the new deployment of small cells.



Source: Mobile Experts

Chart 36: Carrier Unlicensed AP Shipment, Middle-East Africa, 2017-2023

8 COMPANY PROFILES

ACCELLERAN:

Accelleran is a small cell OEM startup based out of Belgium focusing efforts to produce LTE TDD small cells, targeting both licensed bands and shared 3.5GHz CBRS band for the US. At the MWC 2017, the company released its CBRS small cell based on Cavium SoC. The company has a few trials ongoing with cable and OTT operators in the US to pursue potential market opportunities leveraging CBRS. www.accelleran.com

ACCURIS NETWORKS:

Accuris provides software solutions to facilitate roaming in cellular and Wi-Fi networks, and in particular the company focuses on mobile operators to enable authentication, billing integration and policy management services. The experience that Accuris brings in from its mobile customers in roaming solutions will aid in its drive for mobile/Wi-Fi integration. www.accuris-networks.com

AEROHIVE:

Aerohive offers a wide product line, ranging from access points to cloud management solutions. The company's primary focus centers on enterprise customers and identity-based network access. www.aerohive.com

AIRSPAN:

Airspan Networks has developed a line of LTE small cells, including indoor enterprise units and outdoor units with integrated wireless backhaul. The company introduced LTE Relay system to boost network efficiency at cell edge. The company has deployed tens of thousands of small cells in India, as well as successful relationships with Softbank in Japan and with Sprint in the US. With successful small cell deployments, the company has tripled its employee base to pursue growth opportunities in North America, APAC, and MEA. www.airspan.com

ALTAI TECHNOLOGIES:

Altai provides a lineup of Wi-Fi networking solutions that centers on its directional "Super Wi-Fi" access point which is often used in outdoor applications for a long-range coverage. The company has installed systems throughout the developing world for local wireless service providers. www.altaitechnologies.com

ALTICE

Altice is a major mobile/cable operator with operations in France, Portugal, and the USA. After acquiring Cablevision and Suddenlink, Altice has major footprint the tri-state NYC area and Midwest/Texas area. Cablevision has been an active stakeholder in the carrier Wi-Fi space as one of the leading cable operators to adopt Wi-Fi to "extend" its broadband network. Altice along with Cox is believed to have a MVNO partnership with Sprint whereby Sprint is working with the cable operators to install strand-mount small cells in exchange for MVNO access. www.alticeusa.com

APTILO:

Aptilo is a leading vendor in Wi-Fi integration software and services for the mobile core. Aptilo has taken the clear leading market share by serving most of the major mobile operators with Wi-Fi offloading solutions to facilitate billing and policy integration. www.aptilo.com

ARRIS:

Arris is a major cable infrastructure vendor, including CMTS and cable modems. As more Wi-Fi capabilities are embedded into broadband CPEs, Arris is increasingly seen as a trusted supplier of both cable and Wi-Fi equipment to the cable operators. It is reasonable to expect Arris to broaden wireless product portfolio as the cable operators increase their Wi-Fi network footprint and possibly into other wireless technologies in the unlicensed band use. www.arris.com

BAICELLS:

Founded in 2014, Baicells is a privately-held company based in Beijing, China. The company's product solutions range from indoor and outdoor small cells, CPEs, and antennas. With a new sales office in the USA, the company is targeting the WISP market with its outdoor LTE small cells including those that operate in the 3.5 GHz CBRS band. www.na.baicells.com

BOINGO WIRELESS:

Boingo began offering Wi-Fi services to travelers in airports as far back as 2001. They recently signed a Hotspot 2.0 roaming agreement with Sprint that provides Sprint customers access to Boingo's hotspot networks at major US airports. The company is reportedly in a serious discussion with another major US mobile operator for a Hotspot 2.0 roaming agreement. The company has ventured into new businesses for growth including Distributed Antenna System (DAS) for mobile operators and network services to military bases. www.boingo.com

BROADCOM:

Broadcom is one of the leading chipset suppliers in the Wi-Fi market. Most major smartphones and access points use Broadcom chipset. With a broad portfolio of IP and chipset solutions in both mobile and Wi-Fi markets, the company is in a leading position in the carrier infrastructure market. In addition to the Wi-Fi chipset, the company has a product line dedicated to licensed small cells. www.broadcom.com

CHARTER:

Charter is the second largest cable operator in the USA with 24 million household and small business broadband subscribers. Its cable network is expansive with a geographic footprint covering over 50 million households from east to west coasts. With its extensive fixed broadband and Wi-Fi footprint, Charter is expected to launch its mobile service offering in mid-2018. The mobile service offering is expected to be similar to Comcast's mobile service leveraging Verizon's MVNO relationship and relying on Wi-Fi for mobile data offload. www.charter.com

CHINA MOBILE:

As the largest mobile operator in the world in terms of subscribers and network footprint, China Mobile was an early adopter of leveraging Wi-Fi network for mobile data offload. The company has roughly 6 million Wi-Fi access points that can be upgraded, but specific plans for the upgrade have not been announced. With the near-term focus on 5G network rollout and additional C-band spectrum deployment, its carrier Wi-Fi upgrade plan is unclear. www.chinamobileltd.com

CISCO:

Cisco is the leading WLAN equipment provider with extensive global channel partnerships especially in the enterprise segment. Cisco has been moving aggressively to extend its lead into the service provider market with a portfolio of small cell and Wi-Fi access points. Cisco has several active programs to extend its wireless business with service providers beyond Wi-Fi into the unlicensed LTE space. Its recent membership to the MulteFire Alliance is a good guidepost of its intention to be an active player in the evolution of the Carrier Wi-Fi market. Cisco sees the service provider Wi-Fi opportunity as a way to extend its market footprint in the cable and mobile industries. With its broad portfolio of products ranging from core routing and switching extending to wireline and wireless access networks, Cisco can be an influential player in the Wi-Fi / LTE convergence in the unlicensed use. For now, Cisco's wireless strategy is still firmly planted in Wi-Fi and the IEEE 802.11 roadmap. www.cisco.com

COMCAST:

Comcast is the largest US cable operator with over 26M fixed broadband household and business subscribers. The company has been moving aggressively in expansion of its 'xfinity' Wi-Fi service with over 18M homespots and hotspots. Although a majority of its public-facing hotspots are dual SSID from residential CPE's, the company has deployed outdoor units along its cable plant in strategic locations. Leveraging its MVNO agreement with Verizon, Comcast launched its mobile service last year and reports about 600K subscribers. In addition to its mobile play, the company has been actively deploying pre-802.11ax 8x8 MIMO CPE gateways in the homes to improve the wireless performance at subscriber locations. www.comcast.com

COMMSCOPE:

CommScope is a global leader in fiber and wireless systems whose product portfolios ranges from DAS to small cells (from Airvana acquisition). In addition, the company's Comsearch subsidiary is one of the approved SAS providers for CBRS operation. We expect to see the company introduce small cells and DAS products that support CBRS. www.commscope.com

ERICSSON:

Ericsson is a leading vendor of mobile infrastructure worldwide. The company made a big move into the Wi-Fi space with the acquisition of BelAir Networks. Besides the Wi-Fi product portfolio from Belair, Ericsson has a partnership with HPE (Aruba) for cross-selling HPE/Aruba Wi-Fi solutions into the service provider segment. With its broad portfolio of macro, small cell and Wi-Fi products, Ericsson is expected to lead deployment of HetNet solutions into the service provider segment. With its extensive small cell portfolio ranging from outdoor and indoor units, the company has conducted numerous LAA trials and is shipping these units in commercial rollouts. www.ericsson.com

EXTREME NETWORKS:

Extreme Networks acquired a line of Wi-Fi solutions from Zebra, which it sells into large venues. Its Wi-Fi products have been notably deployed at NFL stadiums. And, as an official NFL Wi-Fi analytics company, it has been active in selling Wi-Fi solutions as in-building wireless system into other large venue segments including hospitals and hotels. Extreme is in process of acquiring Avaya assets from bankruptcy. www.extremenetworks.com

FACEBOOK:

Facebook announced its Terragraph open-source project to provide fixed wireless connectivity using the unlicensed 60 GHz spectrum. Similar to Google's ambition of connecting more people to the Internet via low-cost connectivity alternatives, Facebook is working with some major companies to advance the 60 GHz point-to-multipoint ecosystem including Qualcomm, Intel, Nokia, and others. terragraph.com

FEDERATED WIRELESS:

Formed in 2012, Federated Wireless is one of the leading suppliers of Spectrum Access Service (SAS) and ESC platform that is critical in use of the 3.5GHz CBRS band. The company's approach incorporates a network of radio sensors to alleviate possible interference with incumbent users of the band, including naval radars, satellite, and wireless ISPs. The company is headquartered in Arlington, VA, and has strategic investments from key cable players including Charter and ARRIS.

FON:

FON has created a worldwide "crowdsourced" network of Wi-Fi access points where members share access to their residential or small-business Wi-Fi in order to gain access to others. The network has grown to more than 20 million "hotspots" or access points. The company has established partnerships with global telcos including BT, Deutsche Telekom, Softbank, Oi, and Telstra. www.fon.com

FORTINET (MERU):

Fortinet provides a Wi-Fi access point product line that emphasizes security feature. W-Fi AP products are seen as a product add-on to sell its security solution to service providers. Fortinet acquired Meru Networks in 2015. Meru had focused on providing virtualized solutions for the enterprise Wi-Fi market, and with solutions geared for stadiums and other public spaces has developed solutions compatible with Hotspot 2.0. www.fortinet.com

GOOGLE:

In 2015 Google made a move into the Wi-Fi First space announcing Project Fi, a subscriber service. The Google Fi service offers Wi-Fi calling, and falls back to MVNO service when Wi-Fi is unstable or unavailable. Google's MVNO structure is unique in that it allows users to leverage both Sprint and T-Mobile networks. The company continues to make moves into the public Wi-Fi space by backing Sidewalk Labs, which is leading the LinkNYC project to convert old pay phone stands to hotspots in New York City and Google Station project in India where it's establishing free Wi-Fi access at 400 train stations. Moreover, the company

has been leading the 3.5GHz CBRS ecosystem and has developed a SAS system for the use of 3.5GHz CBRS bands. www.google.com

HUAWEI:

Huawei is a global supplier of wireless telecom hardware, and has a leading market share position in licensed-band radio access networks in developing countries. The company has integrated Wi-Fi radio hardware into its "AtomCell" line of licensed small cells and has close relationships in China which all but guarantees a solid market share position as licensed/unlicensed small cells are deployed. Huawei is also a major driving force behind the IEEE 802.11ax standard effort, and is making a strong push in the enterprise WLAN market. www.huawei.com

HP ENTERPRISE (ARUBA):

HP is a major player in the enterprise WLAN market and is overlapping a bit into the carrier Wi-Fi market. With the Aruba acquisition in 2015, HP Enterprise immediately jumped into a top-tier market leader in the Wi-Fi network equipment space. With a special focus on campus-type enterprise product portfolio from Aruba, HPE has made significant inroads in the enterprise segment, including indoor and outdoor campus solutions. Many of the enterprise features can be translated into the service provider segment, and HPE has had success selling into the service provider segment in Middle East and Asia-Pacific. www.hpe.com

INTEL:

Intel provides chipset solutions into smartphone OEMs as well as small cell vendors. Intel is also active in MulteFire and 3.5GHz CBRS development. With its broad reach into smartphone devices, licensed and unlicensed small cells as well as data center solutions, it is in a good position to influence the broader HetNet evolution as service providers look to harness both licensed and unlicensed bands. The company is also one of the leading 60 GHz chipset suppliers in the market along with Qualcomm and Peraso. www.intel.com

MARVELL:

Marvell provides SoCs for the baseband and radio processing for Wi-Fi access points, and has launched an 802.11ac Wave 2 chip with MU-MIMO. The company has acquired Kinoma in an effort to gain traction in the Internet of Things and M2M market. The company refocused its wireless chipset strategy away from targeting mobile devices and is now focused on WLAN infrastructure market especially automotive. The company's 802.11 chipset is going into a variety of applications including Starry's millimeter wave fixed wireless access system. www.marvell.com

MAVENIR:

Mavenir Systems acquired Stoke, and the combined company provides software-based networking solutions that enable carriers to deliver next generation services over 4G LTE networks and "untrusted" Wi-Fi networks. The company has a broad portfolio of LTE and Wi-Fi network elements, and the product lines can be sold "as a service." www.mavenir.com

MEDIATEK:

MediaTek is a fabless semiconductor supplier that has grown its share of the chipset market for smartphone processors through strong penetration of the Chinese "white box" market for handset designs. The company has introduced a 5-in-1 combo chip with LTE, Wi-Fi (up through 802.11ac), camera and video playback, Bluetooth, GPS, and FM transceivers all with concurrent operation. www.mediatek.com

NOKIA NETWORKS:

Nokia's primary business focuses on infrastructure for the macro layer, but the company has jumped into the small cell and Wi-Fi market as well. Nokia is a leading member of the CBRS and MulteFire Alliances, and has a comprehensive small cell offering that supports the various flavors of LTE unlicensed technologies. For the fixed wireless access market, the company is targeting 60 GHz unlicensed gear to "1 Gbps" wireless broadband access. In addition, the company has LTE-based fixed wireless CPE product as well as 5G NR product in the works. Organizationally, the company fixed wireless product group is a part of its Fixed Networks business (along with PON, Cable products). The company's 60GHz PtMP gear appears to be primarily focused on traditional mobile/telco operators looking to provide wireless alternative in denser environments.www.nokia.com

PERASO:

Persaso is an early pioneer in the WiGig 60 GHz technology space. The company is a fabless semiconductor company based in Toronto and with chipset products for client devices as well as 60 GHz point-to-multipoint wireless infrastructure. The company provides millimeter wave chipset solution to a number of fixed wireless access equipment vendors. www.perasotech.com

QUALCOMM:

Qualcomm Atheros is a leading chipset vendor in the Wi-Fi market. In addition to traditional Wi-Fi and LTE small cell chipsets solutions, the company also offers 60 GHz chipset solution which is widely being used by multiple 60 GHz point-to-multipoint vendors to extend this

newly tapped millimeter wave band. Along with its parent, Qualcomm is a major technology supplier into both licensed and unlicensed bands. Qualcomm is a leading vendor of the LAA, LTE-U, and MulteFire technologies. www.qualcomm.com

RADWIN:

Headquartered in Tel Aviv, Israel, Radwin provide a suite of PtP and PtMP radio products for WISP and Carriers. Under the product branding of "JET" series, the company offers 5 GHz 3.5 GHz radio gears for the WISP market. In addition to the fixed wireless access market, the company is positioning its JET products for Smart City and IoT applications to broaden the market appeal. www.radwin.com

REPUBLIC WIRELESS:

Republic Wireless is one of the leading "Wi-Fi first" operators. It provides a full mobile service based on the "Wi-Fi first" business model where it looks to divert traffic onto Wi-Fi first whenever open Wi-Fi network access is available. When Wi-Fi is not available, it falls back to cellular. The company has an MVNO arrangement with Sprint and extended to T-Mobile more recently. They offer service tiers ranging from a free Wi-Fi Only mode to plans with unlimited talk/text & data via MVNO agreements. Currently, users must purchase a phone from Republic. The company has recently broadly expanded smartphone portfolio beyond the Motorola brand with its software innovation that does not require a pre-installation of Republic's "connection manager" software on devices.
www.republicwireless.com

RUCKUS WIRELESS (ACQUIRED BY ARRIS):

Ruckus Wireless is now a wholly-owned subsidiary of ARRIS. The company's focus on adaptive antenna technology to deploy high-capacity, interference-resistant Wi-Fi access points has been favored by many carriers. It has been one of the leading advocates of the 3.5 GHz CBRS ecosystem to provide cellular coverage and capacity indoors by leveraging shared spectrum for neutral-host capable small cells. The company provides a full range of access points, gateways, and now enterprise switching product to the mix (thanks to Brocade merger/spinoff), and is actively targeting the "hybrid" market segments in the 3.5GHz CBRS space. www.ruckuswireless.com

SAMSUNG:

Samsung has deployed millions of CDMA femtocells in North America, with both Sprint and Verizon Wireless. Samsung also supplied picocells for WiMAX networks, so they have easily converted to LTE small cell products, which have been selected by Sprint and a few other operators for ongoing LTE deployment. Most recently, Samsung has partnered with

Qualcomm to support LTE-U/LAA capable femtocells. Samsung has been a key infrastructure supplier for Reliance Jio's LTE rollout and is making headway at several leading carriers in the USA. Samsung has a portfolio of residential, enterprise, and carrier-grade small cells supporting CBRS and LAA. www.samsung.com

SERCOMM:

Sercomm offers residential and enterprise small cells as well as Wi-Fi routers as a Taiwanese ODM. The company has taken the obvious step of integrating their Wi-Fi router and femtocell products together. Recently the company has focused on China and TD-LTE applications, and supplies TD-LTE, FDD-LTE, and dual-mode TD-SCDMA/TD-LTE small cells to that market. The company has also developed CBRS-capable small cell for the North American market. www.sercomm.com

SIKLU:

Siklu has a long history of delivering wireless backhaul solutions to WISPs and carriers. Based in Israel, the company was founded in 2008. It has 70/80 GHz point to point backhaul product as well as 60 GHz PtMP product that is it shipping today. Its E-band point-to-point products are mainly used in wireless backhaul links in fixed wireless access deployments such as C-spire's recent FWA deployment in Mississippi. www.siklu.com

SPIDERCLOUD (ACQUIRED BY CORNING):

SpiderCloud has been successful converting their field trial and early deployments into major customer wins with Vodafone, Verizon, and America Movil. The company is seen as a major player in the enterprise segment with expanding product features and spectrum bands, including LTE-U/LAA, CBRS, MulteFire, etc. The company is focused on enterprise networks, using a centralized controller to coordinate both Wi-Fi and licensed/unlicensed/shared LTE radio nodes. The company has established a key partnership with Cisco, where they work together to outfit the Cisco Wi-Fi APs in the field with "plug-in" modules, and also where Cisco sells the SpiderCloud solution for enterprise opportunities. The company was acquired in 2017 by Corning to supplement Corning's DAS business. www.spidercloud.com

T-MOBILE:

T-Mobile has been aggressive carrier in the use of unlicensed spectrum for its mobile services. With a long history of innovations in the area of unlicensed spectrum use including the early days of Wi-Fi calling implementation with Kineto Wireless, T-Mobile has been an innovator in deployment of personal cell spot Wi-Fi and later LTE femtocells. Most recently, T-Mobile has launched LTE-U/LAA technology to expand mobile coverage and capacity into the unlicensed space. With the merger proposal with Sprint pending, its position in the use

of LAA remains somewhat uncertain as Sprint would bring tremendous amount of the 2.5 GHz spectrum which would presumably diminish the need for the use of unlicensed spectrum. www.t-mobile.com

UBIQUITI NETWORKS:

Ubiquiti has a long history of delivering very low-cost radio gears for the WISP market. Under the AirMax brand, the company offers PtMP fixed access products across many spectrum bands. The AirFiber brand is associated with its wireless backhaul products with long range and capacity. The company has been touting its next-generation "LTU" platform which supports OFDMA (like LTE and 802.11ax) and other features to boost sector capacity and subscriber throughput speed. In the meantime, the company has created successful enterprise Wi-Fi access point product line which is growing faster than its original root in the fixed wireless industry. www.ubnt.com

WI-FI ALLIANCE (WFA):

Wi-Fi Alliance is an industry trade group which promotes the "Wi-Fi" brand, as well as certifying products to be compliant with Wi-Fi standards as well as with Hotspot 2.0 and other requirements. Wi-Fi Alliance provides the "Passpoint" trademark for products which comply with the Hotspot 2.0 requirements. The group is currently in charge of coming up with LTE-U/Wi-Fi coexistence test plan. In a way, it has become a "gatekeeper" to LTE-U deployments in the US. The test plan is now expected to be completed in September 2016. www.wi-fi.org

WIRELESS BROADBAND ALLIANCE (WBA):

WBA is an industry organization made up of a diverse group of service providers, promoting specification and promotion of "carrier grade" services over Wi-Fi networks. The group develops specifications such as the Hotspot 2.0 (also known as Next Generation Hotspot in WBA parlance) to enable seamless interworking on Wi-Fi networks. www.wballiance.com

XIRRUS:

Xirrus offers indoor and outdoor APs for carrier-grade Wi-Fi applications in stadiums and other large venues. The company has developed RF arrays for applications in very high user density environments, and their recent products are Hotspot 2.0 compatible. www.xirrus.com

ZTE:

ZTE offers a complete line of wireless infrastructure products including macro base stations, small cells, and fixed wireless equipment. As one of the major supplier of wireless infrastructure, ZTE provides RAN gear to domestic telecom operators in China as well as select customer base throughout the world. The company offers LTE gear for use in unlicensed bands for WISP market. http://wwwen.zte.com.cn

9 ACRONYMS

2G: Second Generation Cellular

3G: Third Generation Cellular

3GPP: Third Generation Partnership Project

4G: Fourth Generation Cellular

802.1x: A security platform standard established by IEEE.

802.11: An umbrella standard which encompasses multiple unlicensed communications standards within the IEEE.

802.11a/b/g: Early generations of the 802.11 standard.

802.11n: The current generation of the 802.11 standard.

802.11ac: The generation of the 802.11 standard introduced in 2013.

802.11ad: An IEEE standard for 60 GHz short-range communications.

802.11ah: An IEEE standard for unlicensed communications below 1 GHz.

802.11ax: A future IEEE standard for very high throughput in Wi-Fi.

802.11ay: The next-generation 802.11ad that operates in 60 GHz band.

802.11i: An IEEE security specification for Wi-Fi networks.

802.11k: An IEEE standard for radio resource management to assist in limited mobility.

802.11r: An IEEE standard for rapid transition from one AP to another.

802.11u: The IEEE standard associated with Hotspot 2.0.

AAA: Authentication, Authorization, and Accounting (typically refers to the server which performs these functions).

AC: Alternating Current or Access Controller.

ACK: Acknowledgement.

AES: Advanced Encryption Standard.

ANDSF: Access Network Discovery and Selection Function.

Android: Google's mobile device operating system.

AP: Access Point (often referring to Wi-Fi access point)

APN: Access Point Name

ARPU: Average Revenue Per User

BAS: Broadcast Auxiliary Service (internal RF system used by a TV/radio station for backhaul channels from field to station)

BSC: Base Station Controller

BTS: Base Transceiver Station

Bits/Hz/sec: Digital bits transmitted per Hertz of bandwidth per second

CA: Carrier Aggregation

CARS: Cable Television Relay Service (internal microwave systems used by cable and other pay TV operators)

CBRS: Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US

CPE: Customer Premise Equipment (e.g., cable modem, broadband gateway)

dBm: Decibels of power relative to 1mW

DRS: Distributed Radio System

DSL: Digital Subscriber Line

EAP: Extensible Authentication Protocol.

EAP-AKA: EAP via Authentication and Key Agreement.

EAP-SIM: EAP via Subscriber ID Module.

EAP-TLS: EAP via Transport Layer Security.

EAP-TTLS: EAP via Tunneled Transport Layer Security.

EMEA: Europe, Middle East and Africa

eNB: eNodeB, or the radio access node for LTE

EPC: Evolved Packet Core.

ePDG: Evolved Packet Data Gateway.

GAA: General Authorized Access, applicable for the 3.5GHz shared spectrum, the lowest priority access, similar to unlicensed spectrum use

GB: Gigabyte

Gbps/km2: Gigabits per second per square kilometer

GHz: Gigahertz

GSM: Global System for Mobile communications, a 2G radio interface

GTP: GPRS Tunneling Protocol

GW: Gateway (normally referring to a femto gateway)

HARQ: Hybrid Automatic Repeat Request

HetNet: Heterogeneous Network

HEW: High-Efficiency Wireless (now renamed 802.11ax)

HLR: Home Location Register.

HSPA: High-Speed Packet Access

HSPA+: A subsequent evolution of HSPA with higher throughput

HSS: Home Subscriber Server

Hz: Hertz (cycles per second)

IEEE: Institute of Electrical and Electronics Engineers

IETF: Internet Engineering Task Force

IKEv2: Internet Key Exchange (version 2)

IP: Internet Protocol

IPSec: Internet Protocol Security

IPv4: Internet Protocol version 4

IPv6: Internet Protocol version 6

I-WLAN: Interworking for Wireless Local Area Networks.

LAN: Local Access Network

LTE-A: LTE Advanced, a higher bandwidth version of LTE

LAA: LTE-License Assisted Access, a 3GPP-compliant "official" LTE-U technology

LTE: Long Term Evolution, a "4G" radio interface based on orthogonal frequency division multiplexed data

LTE-U: LTE-Unlicensed, an "unofficial" technology to run LTE waveform on 5GHz unlicensed spectrum band

LTTS: Long Television Transmission Service (relay television programming between points)

LWA: LTE/Wi-Fi Aggregation (use of LTE signals on both licensed control channels and licensed data channels, and Wi-Fi signals on unlicensed data channels).

MAC: Media Access Control layer

MHz: Megahertz

MIMO: Multiple Input, Multiple Output

MNO: Mobile Network Operator

MSO: Multi-Service (or System) Operator (reference to a cable operator)

MVNO: Mobile Virtual Network Operator

MulteFire: Standalone LTE-U technology whereby both control and data plane traffic flows in an unlicensed band

MU-MIMO: Multi-User MIMO.

NGH: Next Generation Hotspot (Hotspot 2.0)

OEM: Original Equipment Manufacturer

OFDM: Orthogonal Frequency Division Multiplexed

OFS: Private Operational Fixed Microwave Service (governed by Part 94 of FCC rules)

PAL: Priority Access License, applicable for the 3.5GHz band, second highest priority in use of the 3.5GHz shared spectrum

Passpoint: A certification stamp for Hotspot 2.0 equipment, administered by Wi-Fi Alliance

PC: Personal Computer

QoS: Quality of Service

RAN: Radio Access Network

RF: Radio Frequency

SAS: Spectrum Access System, a software system to coordinate spectrum sharing (although it can be applied across all shared spectrum, its use is primarily focused on 3.5GHz CBRS)

SIP: Session Initiation Protocol

SNR: Signal-to-Noise Ratio

SSID: Service Set Identification

TD-LTE: Time Domain based Long Term Evolution

UE: User Equipment

U-NII: Unlicensed National Information Infrastructure

VAR: Value Added Reseller

W: Watts

WCDMA: Wideband Code Domain Multiple Access, a 3G radio interface

Wi-Fi: Wireless Fidelity (802.11 data communications)

WISP: Wireless Internet Service Provider

WLAN: Wireless Local Area Network

10 METHODOLOGY

To create estimates and forecasts for the Carrier Wi-Fi market, Mobile Experts relied on direct input from more than 70 industry sources, with many different mobile, cable, and ISP operators contributing to the overall analysis to give a detailed global view of the market. Mobile Experts built a "top-down" forecast based on direct input from mobile operators and based on trends in end-user demand for mobile services. Then, Mobile Experts built a "bottom-up" forecast through discussions with OEMs, software developers, and semiconductor suppliers in the supply chain. Roughly 40 suppliers, integrators, and OEMs participated in this phase of the survey. Mobile Experts also used financial disclosures from publicly traded companies to assemble a quantitative view of the equipment market.

Mobile Experts has investigated the entire ecosystem for Wi-Fi in public areas, with segmentation that is different than other market analysis. In this study, we cover Wi-Fi equipment deployed by an "operator", meaning a company that provides a public wireless access service, as well as large venues such as stadiums, airports, military bases, and even city deployments. These non-carrier participants are included because Hotspot 2.0 enables all of these entities to interwork via roaming agreements in the same way, and the equipment is likely to look very similar.

Small cells with integrated Wi-Fi are included in this analysis. In particular, Mobile Experts has assumed that many indoor licensed small cells will also include Wi-Fi semiconductors. This forecast estimates the number of these Wi-Fi APs and the minority portion of the small-cell ASP which is devoted to unlicensed operation.

SCOPE OF CARRIER UNLICENSED RADIO:
A "Carrier Unlicensed Radio" unit can be either an Access Point (AP) or a Customer Premise Equipment (CPE) unit that primarily operates in unlicensed or shared spectrum bands. The Carrier Unlicensed Radio unit can operate using either Wi-Fi based technology such as 802.11 n/ac/ax/ad/ay or LTE-based technology such as LAA, MulteFire, or CBRS/OnGo. Please note that Fixed Wireless Access AP and CPE equipment is not included in this report.

NOTES ON MARKET SHARE:
In the Mobile Experts forecast, "market share" designates the proportion of market revenue for each supplier. "Shipment share" denotes the proportion of total shipments from each supplier. In general, Mobile Experts uses market share for semiconductors and for software because revenue tracking is more straightforward than other measurements. However, in the case of network elements such as Access Points or Wi-Fi networks, the revenue from software and service creates confusion and "shipment share" provides a more trackable, straightforward metric.

Figures 21 through 24 give the detailed definitions for each category of equipment, for regions of the world, and for specific segments of Carrier Unlicensed Radio equipment.

North America:	USA and Canada
Latin America:	Mexico through South America, including Caribbean
Europe:	Western and Eastern Europe, including Russia
China:	China, including Tibet and Hong Kong
Asia Pacific:	India through Australia/Micronesia, excluding China
Middle East/Africa:	Pakistan and Turkey through Africa

Source: Mobile Experts

Figure 21. Detailed Definitions for Regions

EAP-SIM:	Extensible Authentication Protocol-by Subscriber Identification Module. This approach uses the SIM card, generally in a handset, to authenticate the user. An increasing number of tablets include SIM cards to take advantage of this approach.
EAP-AKA:	An extension of EAP-SIM to authenticate a user via Authentication and Key Agreement. In short, this is a variation on EAP-SIM for UMTS 3G mobile devices.
EAP-TLS:	Authentication using Transport Layer Security relies on certificates. The TLS protocol uses certificates from both the end-user device and the network to validate a two-way connection.
EAP-TTLS:	Authentication using Tunneled Transport Layer Security also relies on certificates, but in this case only the network must provide a certificate and the client may be validated through a secured tunnel.

Source: Mobile Experts

Figure 22. Detailed Technical Definitions for Specific Authentication Protocols

LTE Unlicensed	Known as LTE-U. Defined by the LTE-U Forum and led by Verizon in cooperation with Alcatel-Lucent, Ericsson, Qualcomm Technologies, Inc., and Samsung. LTE-U base stations and consumer devices leverage unlicensed frequencies in the 5 GHz (UNII-1 and UNII-3) bands as data channels, with the LTE control plane operating across licensed frequencies. LTE-U is based on 3GPP's already published Release 10 and later specifications. LTE-U extends the benefits of LTE and LTE Advanced to unlicensed spectrum, but without a Listen-Before-Talk schema.
CSAT	Carrier Sensing Adaptive Transmission essentially uses a duty cycle to turn LTE on and off. The duty cycle can be adaptive but many examples refer to a 1/3 duty cycle for LTE transmission.
Listen-Before-Talk	A mechanism for contention mitigation. LBT systems can more fairly share spectrum with heterogeneous standards and not dominate a wireless channel.
Licensed-Assisted Access	Known as LAA. Like LTE-U, LAA leverages unlicensed spectrum for data in the 5 GHz (UNII-1 and UNII-3) bands as data channels, with the LTE control plane operating across licensed frequencies. LAA offers support for Listen-Before-Talk. Ratification by 3GPP is expected in Release 13 in March 2016.
LTE/Wi-Fi Aggregation	Known as LWA. LTE/Wi-Fi Aggregation uses Wi-Fi (802.11ac, etc.) in 5 GHz data channels, with the LTE control plane operating across licensed frequencies. Because it uses standard Wi-Fi protocols, it is less likely to disrupt existing systems. Ratification by 3GPP is expected in Release 13 in March 2016.
Citizen Broadband Radio Service	Known as CBRS. 150 MHz of 3.5 GHz shared spectrum band allocated in the USA for use in TD-LTE primary access or in LAA manner as a secondary cell
MulteFire	Standalone LTE operation in unlicensed band without the need for the "anchor" carrier in a licensed spectrum band.

Source: Mobile Experts

Figure 23. Detailed Technical Definitions of Access Technologies